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An evaluation of the effect of radical negative rake angles on ceramic cutting tool life.

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AN EVALUATION OF THE EFFECT OF RADICAL NEGATIVE RAKE ANGLES ON CERAMIC CUTTING TOOL LIFE

by

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Professor in Charge

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This thesis describes an experimental program that was designed to evaluate the effect of large negative back rake angles on ceramic tool life. The radical negative rake angle concept calls for the grinding of negative angles on the tool, as the means of obtaining large negative back rake angles without reducing edge strength. Four levels of radical negative rake angle are examined -5^{o}, -10^{o}, -15^{o} and -25^{o}. The effects of this treatment on both experimental and commercial tool material grades are examined.

After surveying previous work done in the area of ceramic tool geometry, the author describes a multivariate metal cutting experiment designed to evaluate the effect of radical negative rake angles on ceramic tool life. In this case, tool life is determined by workpiece surface finish criteria. The test involves the use of specially prepared ceramic inserts, in straight turning on normalized 4340 steel.

The experimental data are analyzed using the Analysis of Variance and the Duncan Multiple Range test techniques. The analyses show that increasing radical negative rake angles increase tool life, as determined by surface finish, in this application. Flank wear, crater area, vertical (cutting) and horizontal (thrust) force components also increased with increasing radical negative rake angle.

For the range of rake angles examined -15^{o} was felt to be the optimum. This angle yielded maximum tool life with no sig-

nificant increase in machining forces over those observed for a standard (-5°) insert. It appears that radical negative rake angles force the crater back from the cutting edge, thus improving edge strength.

Significant performance differences are found among the eight tool materials in the study from a tool life standpoint. "Soft" tool materials seem to perform better in surface finish critical operations than do hard materials, since the low hardness tools recorded the highest tool life values.

Tool life is dependent on the condition of the trailing edge of the insert flank wear land, rather than the magnitude of either the flank or crater wear present. The wear mechanisms observed are abrasion, plastic flow and microspalling. Fatigue, creep and chemical wear are also thought to be active.

INTRODUCTION AND OBJECTIVES

This thesis work has been performed as part of the National Science Foundation Hard Materials Research effort which has provided support for research projects at various universities and research facilities in the United States. The particular study to which this work is connected concerns an investigation into the physical properties and performance characterization of various commercial tool materials, as well as the solid solution series Al_2O_3-Cr_2O_3 .

The work documented herein represents an extension of this investigation and has the following objectives.

i) to evaluate the effect of large negative rake angles on ceramic cutting tool life, where tool life is determined by surface finish criteria.

ii) to determine whether some deficiencies that have been noted in cutting tool materials may be compensated for by tool geometry considerations.

This work is aimed at developing and investigating concepts which may ultimately lead to a better, more consistently performing ceramic cutting tool.

BACKGROUND INFORMATION

Historical Developement of Ceramic Tools

Since their introduction to American industry in the mid-1950's, ceramic cutting tools have established themselves as an important element of the tool material spectrum. Although ceramics account for only about 2 - 3% of the total dollars spent on cutting tool inserts, no efficiently run machine shop should be without them.[1] Their combination of high hardness, wear resistance, thermal and chemical stability provide a unique set of physical properties which, when properly applied can yield excellent tool life and surface finish, as well as decreased machining time through higher cutting speeds. This all combines to give ceramics a definite economic edge over carbide and high speed steel tools in some specific applications.

The improved performance of present day ceramic tooling is mainly the result of material and processing improvements. The basic requirements of a good ceramic cutting tool have been known for years. Small, uniform grain size and the elimination of both internal and external flaws are necessary in order to get the required strength, toughness and wear resistance. Better knowledge concerning the preparation of raw materials of the required purity, better methods of controlling the addition of grain growth inhibitors and alloying agents and better control of the kilns and hot presses have led to the improved mechanical properties of today's tools.

Table 1 gives an indication of how far the material engineers have advanced in the past 20 years with regard to ceramic tools. This table is not meant to be a definitive statement on the properties of ceramic cutting tools, but rather it is to serve as an indicator of the advances made in ceramic tool material technology through the years. It also provides a sample of some tools in popular use today and compares the major physical property differences between ceramics and carbides.

TABLE 1. CERAMIC TOOL PROPERTIES

	1957 [2]	1963 [3]	1973 [4]			
			NPC-A2	O-30	VR-97	C-6
Density*(g/cm^3)	3.92-3.95	3.98	4.24	4.09	3.97	14.9
E (10^6 psi)	60	60	60	60	60	80
TRS (ksi)	75	90	103	90	100	250
Comp. Str.(ksi)	400	500	570	505	450	610
Microhardness	92 - 95	93	94	1665	1655	91
	R_{15N}	R_A	R_A	(Knoop)		R_A
Additions		MgO TiC	MgO	TiO	MgO	

* Theoretical density of pure Al_2O_3 = 3.97 g/cm^3

Improvements in ceramic cutting tool performance will no doubt be made through future refinements in material preparation, processing and alloying. One area of potential improvement in ceramic tools that seems to have been overlooked by most manufacturers is that of edge strength increases through tool geometry control and edge preparation. Some of the more influential work in this area will be reviewed.

Tool Geometry

The tool geometry of a disposable ceramic insert is determined by the shape of the insert and the toolholder being used. The principle components of tool geometry and the components of machining force for an SNG insert are shown in Figure 1.

The back rake and end relief angles shown in Figure 1a will be equal for an SNG insert. Both of these angles affect the apparent strength of the insert in machining. This is possible, in the case of the back rake angle, through its effect on the shear plane angle and cutting forces. Increasing negative rake angles tend to increase the shear plane angle and so the cutting forces for a given depth of cut, loading the tool more in compression than in tension. As can be seen from Table 1, the compressive strength of most ceramic tools exceeds the tensile strength by a ratio of roughly 5 to 1, so that a compressive loading is preferred.

Ceramics can be used most effectively at high cutting speeds with negative rake angles since they are one of the few tool

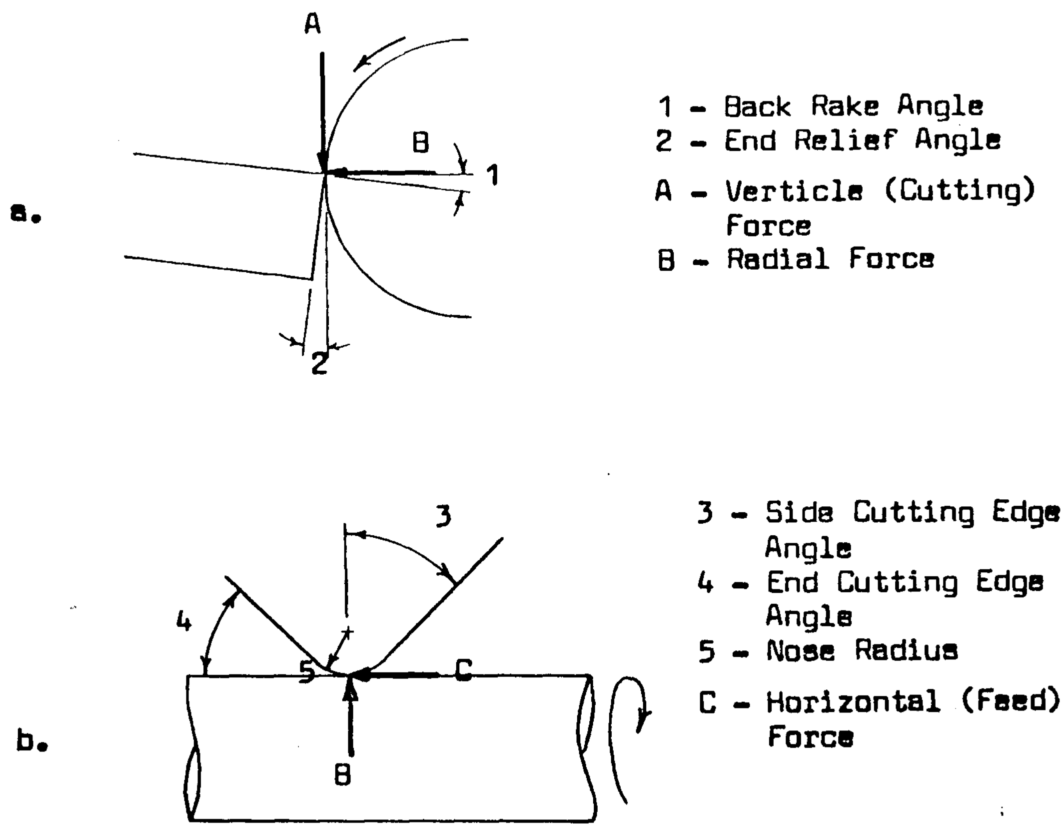
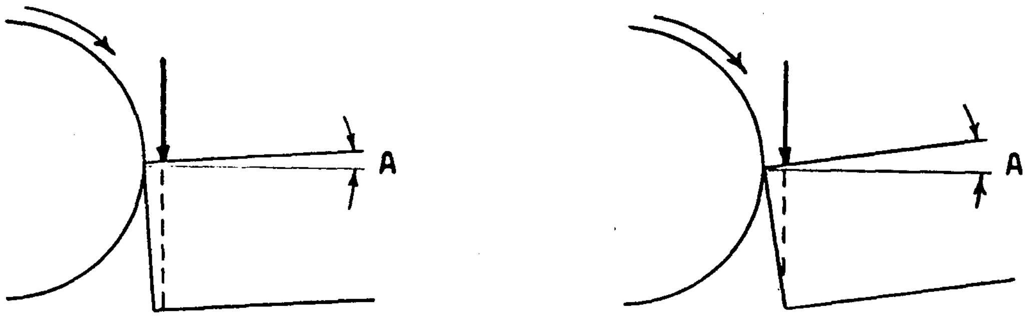


FIGURE 1. COMPONENTS OF TOOL GEOMETRY AND MACHINING FORCE



$A = 5^{o}$
Back rake and
End relief

$A = 10^{o}$
Back rake and
End relief

FIGURE 2. THE EFFECT OF END RELIEF ANGLE ON A TOOL'S BACKING RESISTANCE TO APPLIED VERTICAL LOAD

materials available that can withstand the effects of the accompanying high temperature.[5]

Large negative rake angles interact with the high cutting speeds normally used with ceramics to give extremely high temperatures, on the order of 800 - 1000^{o}C, in the thin layer of the chip near the tool face. These high temperatures reduce a tool's mechanical properties, but can also lead to reductions in the shear strength of the workpiece material which in turn lowers the frictional and vertical force components of cutting. The shear strength of ferrous materials begins to decrease beyond 300^{o}C.[6]

The end relief angle of an SNG disposable insert is determined by the back rake angle, or vice versa, depending on which is more important. It affects tool strength by determining the backing resistance for the applied cutting load, as shown in Figure 2.

For an SNG insert, changing the rake angle to make it more negative improves tool strength through increased compressive loading. However, the accompanying increase in end relief angle exposes less of the tool point to the applied tensile load, making gross tool tip fracture more likely. Obviously some optimum combination of the two is required when dealing with disposable inserts.

As can be seen in Figure 1a, a small end relief angle exposes more of the tool flank to the rotating work-piece. This increases tool-workpiece friction leading to higher radial and vertical forces as well as increased temperature.

The side cutting edge and end cutting edge angles, shown in Figure 1b, are equal for an SNG insert. The side cutting edge angle determines how much of the tool edge will be exposed to the cutting load. The larger this angle, the greater is the length of cutting edge immersed in the workpiece. Side cutting edge angles (greater than 0°) reduce cutting edge pressure and increase radial forces.

The end cutting edge angle is similar to the end relief angle. It is a determinent of workpiece surface finish and the amount of tool-workpiece contact along the tool flank.

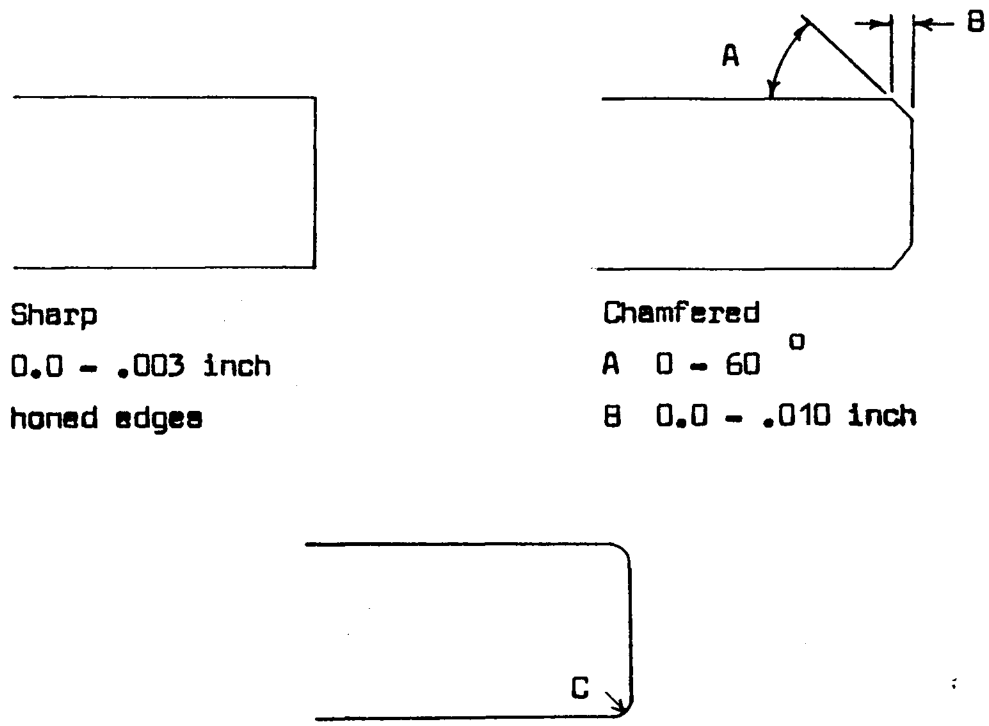
Tool strength, surface finish and radial forces are all functions of a cutting tool's nose radius, also shown in Figure 1b. As the nose radius increases, a more rounded (as opposed to a sharp) profile is presented to the cutting load. More material carries the applied load at a lower unit pressure.

For a given feed rate, a larger nose radius yields a better surface finish, as the feed grooves produced on the workpiece will be wider and shallower.(Assuming that chatter does not occur)

As with the end relief and end cutting edge angles, there is a penalty for exposing more of the tool to the cutting load. Increasing the nose radius increases tool-workpiece friction and so, the radial force. If the radial force gets large enough, and chatter results, ceramic tool failure could be brought on very rapidly by accelerated fatigue processes.

Conditions at the Cutting Edge

The preceeding discussion of tool geometry was for an insert with a "sharp" edge. Much support has been given to the notion of using ceramic inserts in the chamfered or rounded edge condition. Cross sections of the three commercial edge configurations are shown in Figure 3.



Sharp
0.0 - .003 inch
honed edges

Chamfered
A 0 - 60°
B 0.0 - .010 inch

Rounded
C 0.0 - .008 inch

FIGURE 3. CERAMIC EDGE CONFIGURATIONS AND TYPICAL DIMENSIONS FOR SNG - 43X INSERTS

The alternative edge configurations shown were developed in order to control the edge chipping that plagued early ceramic tools. It was felt that extremely high negative rake angles at the cutting edge would enhance the compressive loading of the tool at the edge, thus compensating for their weakness under tensile loading conditions.

The importance of keeping the immediate vicinity of the cutting edge in compression to minimize edge failures can be seen in Figure 4.

Even using negative rake angles, the edge of the sharp tool shown would be subject to substantial tensile forces and the possibility of chipping.

The tensile loading on the chamferred tool has been altered such that compressive forces act on all faces of the cutting edge. The chamferred tool exposes more area to the applied load so as to minimize stresses and distribute them more evenly over the load bearing area of the tool tip.

During cutting the tool tip is immersed in the workpiece, a plastic medium, and subjected to high pressure conditions on all of its contacting surfaces. This is shown schematically in Figure 5.

These restraining forces constitute a hydrostatic loading which causes the mechanical properties of a ceramic tool to differ from those at atmospheric pressure. It has been shown that the strength of ceramic materials can be increased and their ductility

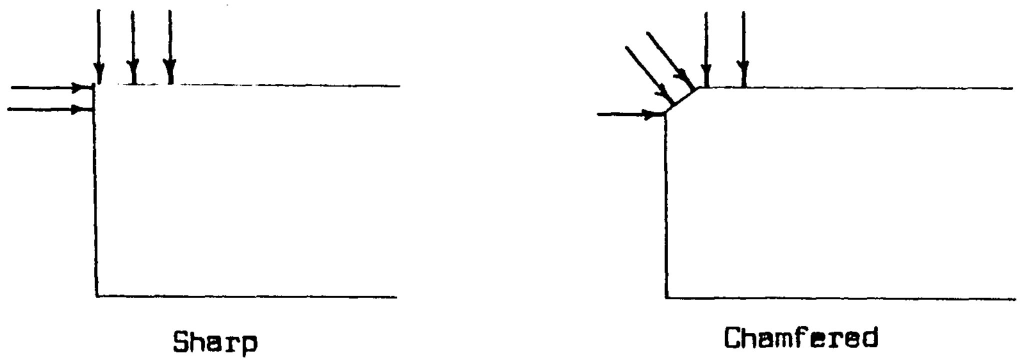


FIGURE 4. EFFECT OF EDGE CONFIGURATION ON TOOL NORMAL FORCES

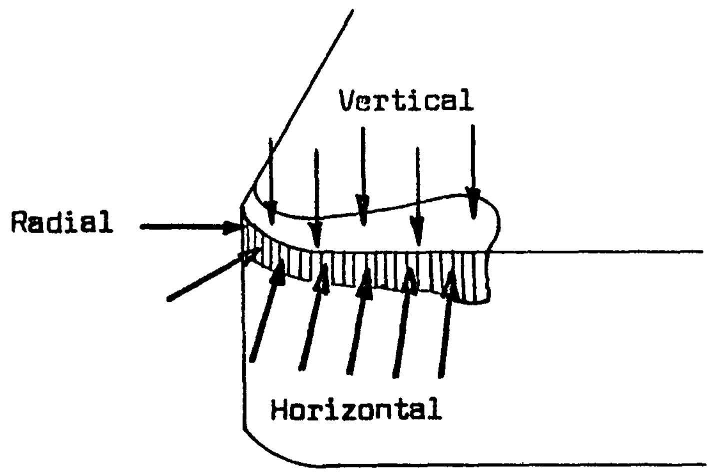


FIGURE 5. TOOL TIP SUBJECTED TO RESTRAINING FORCES[7].

enhanced if mechanical property testing is done under a superimposed hydrostatic load.

The hydrostatic pressure conditions present during machining and the negative tool geometries normally encountered with ceramic tools produce a compressive loading on the tool tip, which tends to retard crack formation through increased plasticity. This increases the compressive strength of the tool beyond that measured by conventional test set-ups. Since crack propagation is such a critical consideration when dealing with brittle materials, the importance of eliminating or minimizing the tensile loads on ceramic tools is now more obvious.

Previous Work

In 1957, shortly after the American introduction of ceramic tools, a number of papers were presented in the literature concerning the effects of altered tool geometry on ceramic tool life and performance.

One of the early research efforts in this area was conducted by H.D. Moore and D.R. Kibbey, then of Ohio State. They presented the results of an experimental program to evaluate the effects of a negative edge land on ceramic tool performance.[9] In their experiment they varied the angle at which the negative land was ground and the width of the land. Experimental levels for each variable were;

Land width .002, .005, .010 inch

Land angle 10°, 40°, 70°

Feed rate was also varied.

One of the reasons that negative edge lands were considered was that during some preliminary testing using tools with no lands, one of the best performing tools developed a small cutting edge chip early in a test. The tool seemed to exhibit almost indefinite life, suggesting that the chip served to correct the existing geometry.

A statistical analysis of the experimental data indicated that tool life was more significantly affected by the land width than by land angle and that there was a strong interaction between the two factors. Although an optimal combination of land width and angle was not found, a strong recommendation was made for their use. "For satisfactory tool life an edge land is essential. The use of even the smallest land was more effective than the wide variety of other conditions tested."

In a paper entitled, "What angles are best for oxide cutting tools?", H.J. Siekmann and L.A. Sowinski examined the effect of tool geometry on ceramic tool life.[10.] "Recent experience shows that the geometry of carbide tools is not suitable for ceramic tools. Extensive tests indicate greater life and efficiency with considerably different angles."

They examined all components of tool geometry in machining tests at constant speed, feed and depth of cut. In five of their seven tests they used tools with a .002 X 45° honed edge to eliminate edge chipping.

The optimum tool geometry as determined by their analysis was -20° back rake angle, -10° side rake angle and 10° relief angles. This combination would not be possible on an indexable insert however. Optimum geometry for standard disposable inserts would therefore be -10° back and side rake angles and 10° relief angles. It should be noted that both of these geometries are different from the standard -5° geometry generally used for carbides and ceramics.

A.O. Haeme and R.T. Hook reported on some industrial applications of ceramic tools and had the following conclusions.[11.]

"The use of a negative land on the side cutting edge, 30° from the vertical of the workpiece and ground to a width representing 80% of the feed rate gives a definite improvement in tool life."

"We feel that more thought should be given to tool holder geometry to offset the weaknesses of ceramics."

The state of the art of machining with ceramics was summarized in 1963 by the book, "Ceramics in Machining Processes," written by A.G. King and W.M. Wheildon.[12.] In the portion of their book devoted to tool geometry, the authors acknowledged the advantages of using large negative rake angles with ceramic tools.

Unlike carbide tooling which tends to get too hot and form built-up cutting edges when large negative rake angles are used, ceramics not only gain in strength but also maintain excellent surface finishes as negative back rake angles are increased. A ceramic tool's low affinity for ferrous metals all but eliminates built up edge problems even under the most severe machining conditions.

The use of side cutting edge angles was recommended as a means of reducing impact loading at the start of cutting as well as edge pressure during the cut. Because of the relatively low tensile strength of ceramic tools, cutting edge pressure is a critical consideration. Thin chips extended over a greater length of cutting edge are advantageous, if the machine tool and workpiece have sufficient rigidity to withstand the higher radial forces that will result.

The work of Moore-Kibbey and Siekmann-Sowinski was reviewed and recommendations for the use of edge lands were made as follows;

1. On steel where feed is above .010 inch
2. On steel if the depth of cut is above .0625 inch
3. On all heat treated steel cuts harder than Rc 40
4. On all cast iron stock removal cuts

In addition to the ground edge lands, originally suggested by Moore and Kibbey, edge radii of .003 - .008 inch created by tumbling in an abrasive medium were suggested as a possible edge configuration.

The use of some edge preparation, other than the sharp edge, was recommended as a means of improving the edge strength of ceramic tools. Ground lands and tumbled radii both have particular applications to which they seem best suited, but either one is preferred to a sharp edge for general use.

Also presented were some specialty tools, which merit attention.

An indexable tool developed by H.J. Siekmann for machining hardened steel in the Rc 60-63 range is pictured in Figure 6.[13.] Machining recommendations were for a speed of 600 sfpm, up to .030 inch depth of cut and a .005 ipr feed. These conditions kept the machining load entirely on the high negative rake portion of the tool and resulted in a tool capable of finishes in the 30 - 80 microinch range at 600 sfpm.

Another interesting tool that was developed by F.L. Bagley Jr. working in conjunction with King and Wheildon, is pictured in Figure 7.[14.] It was designed for rapid stock removal of high-strength, high-hardness steel.

Using this tool in a standard double - negative 5^{o} and 5^{o} toolholder, some excellent performances were obtained machining Rc 52 manganese steel. A tool life of 52 minutes was obtained cutting at 400 sfpm, .005 ipr and .030 inch depth of cut. Extremely strong, this tool withstood feed and radial forces in excess of 1000 pounds, while machining at .080 inch depth of

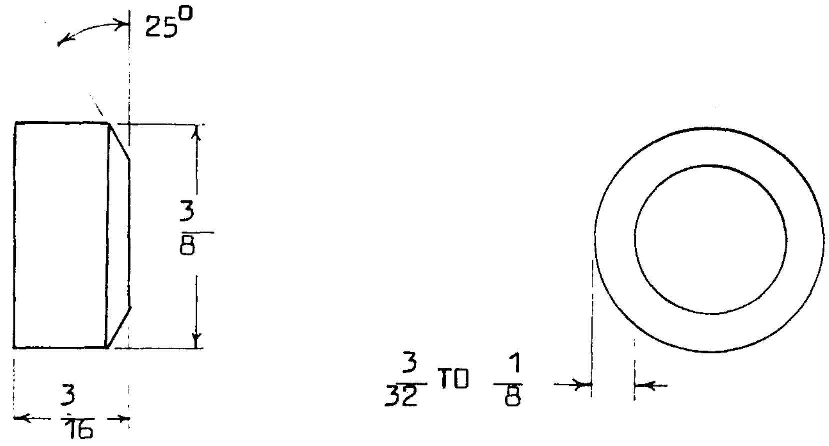


FIGURE 6. THE SIEKMANN TOOL

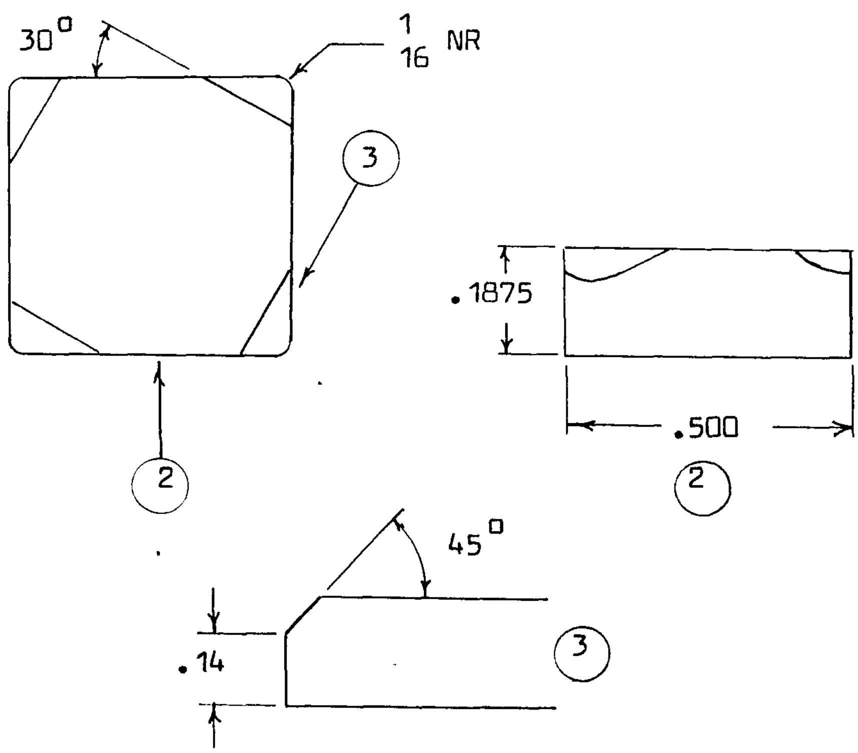


FIGURE 7. THE BAGLEY TOOL

cut and 1000 sfpm.

One last approach to improving tool strength involves the negative edge land discussed previously and chemical polishing. This edge preparation was developed by John C. Logan in cooperation with King and Wheildon, and was termed the "Logan land." Tools which had 60° X .006 inch lands ground on them were chemically polished in a borax fusion at $850^{\circ}C$ for a minimum time so as not to alter the edge configuration.

These chemically polished tools displayed reproducible tool lives of three to four times that of tools having the same edge configuration, but without the chemical polishing, when machining hardened steel in the Rc 48 range.

The speculation was that chemical polishing removed the surface damage resulting from the finishing and other grinding operations performed on the tools. The elimination of surface microcracks, by a method which causes no surface damage itself, increases the strength of a brittle material such as a ceramic tool. The strength increase from polishing coupled with the edge strength improvements from the negative land evidently produced an extremely good cutting tool.

To the present time no new ideas have been presented on the subject of ceramic tool edge preparation. Negative edge lands seem to be generally accepted as the route to improved edge strength and performance with ceramic tools, yet to the author's knowledge only a few suppliers offer tools for sale in this configuration with most offering only the sharp edge with a .001 - .003 inch hone.

The edge preparation techniques that have evolved over the last twenty years seem to have gone largely unnoticed by manufacturers. Perhaps the economies involved are the controlling factor, however tool life improvements of up to 300% by any measure of the term would seem to be hard to ignore.

DESIGN OF EXPERIMENT

Radical Negative Rake Angle Cutting Tools

Description

The program to evaluate the effect of radical negative rake angles on ceramic cutting tool life was initiated by Professor G.E. Kane of the Industrial Engineering Department and Doctor D.P.H. Hasselman of the Metallurgy and Materials Science Department. Citing the reported successes in the use of negative rake angles and edge lands in improving ceramic cutting tool performance, it was decided to design a tool that would combine the best aspects of geometry and edge preparation considerations in a disposable insert. The radical negative rake angle tool design is shown in Figure 7.

When held in a standard -5° toolholder, negative rake angles of as high as 25° are obtainable, without sacrificing a small 5° end relief angle. The negative geometry should improve overall tool tip strength, as the entire machining load will be carried on the negative rake portion of the tool, as was the case with the Siekmann and Bagley tools discussed previously, thus keeping the tip in compression.

Preparation

The radical negative rake angle tools were prepared from standard SNG-433 ceramic inserts. Six commercially available grades and two experimental grades were used in the analysis.

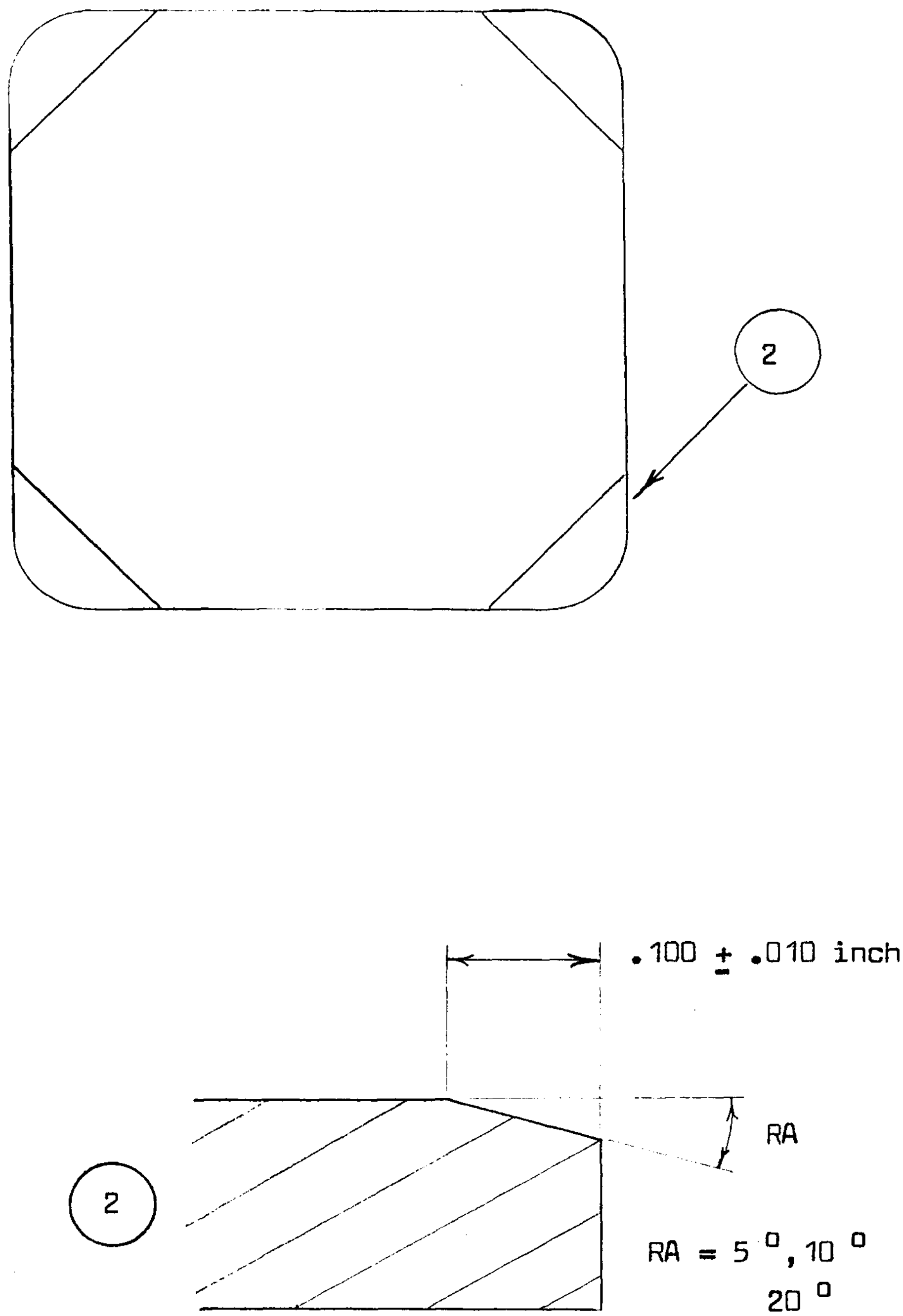


FIGURE 7A. SNG-433 CERAMIC INSERT WITH RADICAL NEGATIVE RAKE ANGLE

Insaco, Inc., an industrial firm specializing in high precision finishing of ceramic materials, performed the necessary work to put negative rake angles on four corners of the insert. Corners were ground to the required configuration and tool edges received a .001 - .003 inch radius hone consistent with industrial practice.

Experimental Design

Independent Variables

A two factor experimental design with three replicates at each condition was used to evaluate the effects of radical negative rake angles and tool material on ceramic tool life and performance. The levels of each independent variable are given below.

Negative Rake Angle: -5°, -10°, -15°, -25°

(includes the -5° from the toolholder)

Tool Material: 5% Cr_2O_3*, VR - 97, O-30, O-30 HP*

Ford 1½ % Mo, CO6, CCT-707, Degussit

* Experimental grades of tool material

A short description of the eight cutting tool materials is given in Table 2.

Dependent Variables

The dependent variables that were measured in this experiment fell into two major categories, tool performance variables and process variables. The measures of each are given in Table 3.

Material Designation	Manufacturer	Composition	Method of Preparation
VR - 97	V/R Wesson Co.	99.9% Al_2O_3 0.1% MgO	Hot pressed
CCT - 707	Carborundum Corp.	99.9% Al_2O_3 0.1% MgO	Hot pressed
5% Cr_2O_3	Lehigh	94.9% Al_2O_3 5% Cr_2O_3 0.1% MgO	Hot pressed
O-30 HP	Lehigh, from O-30 powder	90% Al_2O_3 10% TiO	Hot pressed
O-30	Carboloy Div. General Electric	90% Al_2O_3 10% TiO	Cold pressed and sintered
Ford 1½	Ford Motor Co.	98.5% Al_2O_3 1.5% Mo	Cold pressed and sintered
CO6	Kennametal Corp.	99.9% Al_2O_3 0.1% MgO	Cold pressed and sintered
Degussit	Degussa	99.9% Al_2O_3 0.1% MgO	Cold pressed and sintered

TABLE 2. CERAMIC TOOL MATERIAL DESCRIPTIONS

Tool Performance Variables	Method of Measurement
1. Tool flank wear	Toolmakers microscope
2. Tool crater wear	Optical comparator and planimeter
3. Tool life	Surfindicator
Process Variables	
1. Vertical force	Both force components measured by a tool post dynamometer and two channel recorder
2. Horizontal force	

TABLE 3. DEPENDENT VARIABLES AND METHODS OF MEASUREMENT

All of the variables listed are common measures of performance when dealing with machining experiments. The only one that needs clarification is tool life. For the purposes of this experiment, tool life is defined as that amount of machining time for which a given cutting edge produces a surface finish on the workpiece of 63 microinches or less and resists fracture.

The objective was to simulate production finishing in this analysis, since ceramic tools are used predominantly in finishing operations. A 63 microinch surface finish is an industrial standard for this type of operation.

Constants

The constants in this experiment were tool geometry (excluding back rake angle), machining speed, feed and depth of cut. Consistent with the objective of simulating production finishing the levels chosen for the independent variables are given below.

Tool geometry:	RA, -5°, 5°, 5°, 15°, 15°, 3/64 (SNG-433)
Speed:	750 sfpm
Feed:	.006 ipr
Depth of cut:	.050 inch

Workpiece material was AISI 4340 steel heat treated to Rc 35 ($\pm$ 2). It was felt that this material would typify some of the workpiece materials to which ceramic tools are applied, as well as providing enough machining difficulty to yield discriminating test results.

Although it is rarely possible to keep workpiece material constant, the variation should be kept as small as possible. Due to the amount of machining required for this analysis, it was necessary to change not only workpieces, but also heats of material. In all cases heat treatments were similar, but cannot be claimed to be exactly the same. Any workpiece variations that were present are randomized among the cuts so that there should be no systematic error in the results.

The hardness ranges for the various heats of material used as well as additional information concerning the material are given in Appendix A.

Experimental Procedure

The generation of ceramic tool performance data was accomplished by a continuous lathe turning operation, operating at the previously specified machining conditions on a scale free workpiece. Bar stock, initially 6" X 72", was turned down to a diameter of approximately 3" or until chatter was encountered.

After the first minute, and at two minute intervals thereafter, cutting was stopped and the insert removed so that flank wear , crater area and surface finish readings could be taken. As was mentioned previously a cutting test was concluded when the workpiece surface finish was shown to exceed 63 microinches for an individual cut, or the tool tip fractured.

Machine center height was set-up for an SNG-433 insert in standard configuration. Adjustments were necessary for those tools that had negative rake angles ground on the corners to bring the new cutting edges up to center. Metal shims of the proper thickness were used under the toolholder to raise the radical negative rake angle tools to the proper height.

Center height adjustments, based on geometry considerations, were as follows.

Tool	Adjustment
-5^{o}	0.0 inch
-10^{o}	.010 inch
-15^{o}	.016 inch
-25^{o}	.033 inch

Equipment and Instrumentation

Processing and measuring equipment of the Manufacturing Processes Laboratory at Lehigh University were used to perform the experimental work. The equipment included:

1. A Lodge and Shipley 20 HP, 16"X54" engine lathe.
2. A Stewart Warner hand held tachometer was used to obtain readings of constant surface feet by measuring the rotating speed of the workpiece.
3. A Bausch and Lomb toolmakers microscope was used to measure flank wear.
4. A Jones and Lamson Optical Comparator and a Keuffel and Esser Compensating Polar Planimeter were used to obtain crater area measurements. The optical comparator was used to make tracings of the crater outline (magnification 2500X). The area of these tracings was measured in square inches using the planimeter.
5. A strain-gage dynamometer coupled to a two channel strain amplifier recorder gave measures of the vertical and horizontal force components encountered during machining. The strain gage dynamometer was manufactured by Cook, Smith and Associates and the recorder was a Sanborn unit.
6. A Brush Surfindicator was used to measure workpiece surface finish, using a cutoff width of .030 inches. All measurements were arithmetic average (AA) surface

roughness.

Experimental error estimates for the four measurement devices are given below.

Device	Expected Error[15.]	Experimental Error*
Microscope	.001 inch	.0006 inch
Comparator and Planimeter	no estimate	.173 inches^2
Dynamometer and Recorder	F_V = 10 pounds F_H = 5 pounds	13.4 pounds 8.2 pounds
Surfindicator	8 - 16 microinch	no estimate

* Error estimates are taken to be the square root of the error mean square from a four way ANOVA. Due to the fact that this experiment deals with essentially four different groups of tool materials, error estimates were taken from another analysis. The other analysis involved the comparison of 15 different ceramic tools, all of which had been run through an identical matrix of cutting conditions. All measurements in the other analysis were made in exactly the same way as those for the negative rake tests.

RESULTS AND ANALYSIS

Feasibility Phase

The objective of this phase of testing, was to determine whether the radical negative rake angle concept, which seemed promising in theory, would produce appreciable increases in tool life under actual machining conditions.

Two tool materials, the commercially available VR - 97 and the experimental Lehigh 5% Cr_2O_3, were prepared with radical negative rake angles. These tool materials were chosen for two reasons.

1. They represented both commercial and experimental tool materials.
2. They represented opposing ends of the ceramic tool performance spectrum as determined by W.C. Smith in a previous analysis.[16]

Both tool materials, in each of four radical negative rake configurations, were run through a matrix of cutting conditions at the following levels.

Two levels of cutting speed - 750, 1000 sfpm

Feed - .006 ipr

Depth of cut - .050 inch

Two replicates at each condition

All of the previously mentioned dependent variables were measured.

Machining results for these tests are given in Appendix B with tool life results also summarized graphically in Figure 8.

Two observations can be made from Figure 8.

1. Tool life, as defined by the surface finish criterion generally increased as the radical negative rake angle was increased.
2. Tool life is affected more by changes in rake angle when cutting at 750 sfpm, than it is at 1000 sfpm.

The only exception to these observations was encountered with the 5% Cr_2O_3 tool material, during cutting at 750 sfpm. Increasing the negative rake angle from -5° to -10° produced a decrease in average tool life. If one examines the data it is seen that this decrease is due to premature tool fracture during one of the replicates at -10°. This was the only fracture failure to occur during testing at 750 sfpm, so that the decreased tool life probably represents a chance occurrence rather than a contradiction in results.

Generally, the VR - 97 tool material appeared to respond more positively to the radical negative rake angle treatment than did the 5% Cr_2O_3 tool material. In testing at 750 sfpm, the change in negative back rake angle from -5° to -25° produced an improvement in average tool life from 10 to 34 minutes for the VR - 97 tool. At 1000 sfpm the improvement was from 10 to 19 minutes.

The 5% Cr_2O_3 tool material outperformed the VR - 97 material from a tool life standpoint, at all but the -25° back rake angle

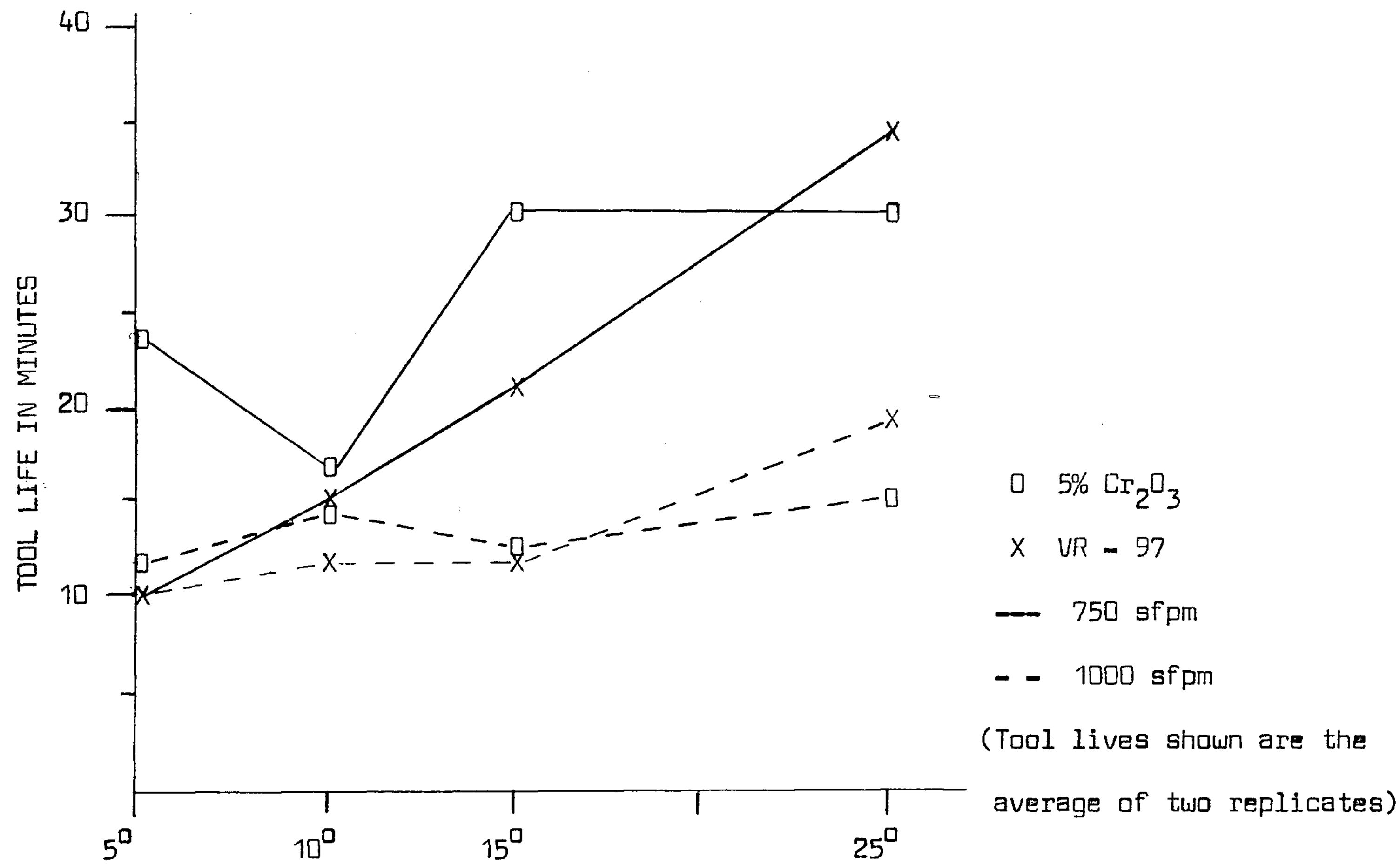


FIGURE 8. TOOL LIFE AS A FUNCTION OF NEGATIVE RAKE ANGLE

for both cutting speeds in this analysis. This is especially interesting, since in the previously mentioned ceramic tool performance analysis, where performance was judged by tool wear, cutting forces and surface finish over a 9 minute period, the 5% Cr_2O_3 tool material performed very poorly relative to the VR - 97. This analysis showed two tool materials that performed very similarly, not only from a tool life standpoint, but also on the basis of tool wear (see Appendix B) , suggesting that perhaps some tool material deficiencies can be compensated for by proper tool geometry, in this case the use of radical rake angles.

The tool life values obtained from tests with the 5% Cr_2O_3 tool material at 1000 sfpm are determined largely by tool tip fracture, rather than by violation of the surface finish requirement. Table 4 shows the frequency of fracture for the 5% Cr_2O_3 material during cutting at 1000 sfpm.

	-5°	-10°	-15°	-25°
Rep 1	X	X		X
Rep 2	X			

TABLE 4. 5% Cr_2O_3, 1000 SFPM, X - INDICATES FRACTURE

In half of these tests, the crater of the 5% Cr_2O_3 tool material fractured at some time during cutting. The VR - 97 tool experienced no fracture failures at these conditions.

Both tool materials produced extremely hazardous continuous chips during cutting at 1000 sfpm, especially at the -15° and -25° rake angles. These chips wrapped around the toolholder, chipping the exposed edges of the cutting tool and also at times around the workpiece, which necessitated stopping in the middle of a test to remove the chips. It was then necessary to restart the cut in order to fulfill the two minute machining time between measurements. These restarts added unnecessary mechanical shocks to the tool tip, that could have caused a reduction in tool life.

The conclusions drawn from the feasibiltiy phase of testing were;

1. The use of radical negative rake angles can yield appreciable increases in tool life, where tool life is defined by surface finish criterion.
2. Testing at 1000 sfpm confounds the effect of radical negative rake angles due to problems with chip control and tool fracture. Future testing should be carried out at 750 sfpm.
3. Three replicates should be performed at each condition in an attempt to reduce the scatter in experimental results.

Evaluation Phase

The objective of this phase of the study was to expand to eight, the number of tool materials tested and then to evaluate the effect of radical negative rake angles on tool life, for a representative cross-section of ceramic tools.

The eight tool materials tested represented not only commercial and experimental grades of tool material, but also were equally divided among four general categories into which ceramic tools can be grouped. Classification can be performed by composition, either straight Al_2O_3 (plus minute amounts of a grain growth inhibitor such as MgO) or Al_2O_3 plus major additions of a second phase alloying element such as the TiO, Mo, and Cr_2O_3 found in the tool materials of this study. Classification can also be based on processing method, with tools being either vacuum hot pressed or cold pressed and sintered. Figure 9 shows the distribution of the eight tool materials among these four categories.

	Cold Pressed	Hot Pressed
Straight Al_2O_3	C06 Degussit	VR - 97 CCT - 707
Multi-Component	O-30 Ford 1½ % Mo	O-30 HP 5% Cr_2O_3

FIGURE 9. CERAMIC TOOL MATERIAL CLASSIFICATIONS

Based on experience during the feasibility phase of testing, the 1000 sfpm cutting speed was dropped and all tool materials were evaluated at 750 sfpm only, with a .006 ipr feed and .050 inch depth of cut, as described previously. Machining data for the evaluation phase is given in Appendix C. (Since this evaluation is concerned primarily with tool life, only endpoint machining data is given. Measurements of the dependent machining variables were made at two minute intervals during all individual tests. This data did not enter the analysis however and so it will not be given.)

Analysis of Variance

Machining data obtained from the evaluation phase was analyzed using the analysis of variance (ANOVA) technique to determine the effects of changes in negative rake angle and tool material on the results (final measures of the dependent variables).

Basically, the ANOVA technique consists of classifying and cross-classifying statistical results and testing whether the mean values of a specified classification differ significantly. In this way it is determined whether the given classification, in this case rake angle or tool material, is important in affecting the results.[17.] A short description of the ANOVA technique is given in Appendix D.

The statistical analysis of the machining data contained herein, was performed using the LEAPS (Lehigh Amalgamated

Package for Statistics) statistical package that is on permanent file on Lehigh University's CDC 6400 computer.

Table 5 gives the endpoint mean values of the dependent variables in this study by factor and level, for the data contained in Appendix C.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Area ($X2500in^2$)	F_V (lb)	F_H (lb)
5% Cr_2O_3	24.5	15.2	2.11	177.3	138.9
VR - 97	25.7	15.5	2.22	184.2	133.4
O - 30	26.8	13.6	2.20	178.2	121.0
O - 30HP	23.8	13.1	2.24	172.9	123.1
CCT-707	44.0	16.9	2.54	181.2	128.7
CO6	24.8	13.0	2.29	182.0	120.7
Ford 1½	27.2	14.2	2.30	177.2	124.2
Degussit	31.5	14.5	2.52	177.3	117.6
5^o	21.0	12.5	2.03	169.8	113.1
10^o	26.7	13.9	2.30	173.0	116.1
15^o	34.0	15.4	2.45	178.7	125.1
25^o	32.5	16.2	2.43	193.7	149.5
Grand Avg.	28.5	14.5	2.30	178.8	125.9

TABLE 5. ENDPOINT MEAN VALUES OF DEPENDENT VARIABLES BY FACTOR AND LEVEL

The two-way ANOVA tables for tool life, flank wear, crater area, vertical and horizontal force corresponding to the mean values given in Table 5 are given in Tables 6-10. Examination of these tables yields some understanding of the effect of radical negative rake angle and tool material on the results.

Use of an F-test shows that both main effects (rake angle and tool material) significantly* affected the observed values of the dependent variables, with two exceptions. First, tool material apparently had no effect on the values of vertical force that were observed. More importantly, rake angle was shown to have no effect on flank wear. This is rather puzzling, as rake angle was significant for each of the other four dependent variables examined. Also, Table 5 shows uniformly increasing values of average flank wear, with increasing negative rake angle and it seems logical to expect higher measures of flank wear with increased rake angle and average tool life.

A possible explanation for this lack of significance is the risk that one takes in performing an F test. The tests in this study were all carried out at the 95% confidence level, which

---

* Statistical significance implies that the mean values of the dependent variables computed for each factor cannot be said to be from the same population. In other words the differences existing between mean values are the result of some causal system and not just experimental error, in 95% of the tests conducted.

ANOVA TABLES FOR DEPENDENT VARIABLES

TABLE 6. TOOL LIFE

Effect	Sum of Squares	df	Mean Square	F - ratio
A - Rake Angle	2540.5	3	846.8	5.61 (3.88)
B - Tool Mat'l.	3756.5	7	536.6	7.86 (2.17)
A X B	3170.8	21	150.9	2.21 (1.74)
Error	4368.0	64	68.2	
Total	13835.8	95	145.6	

TABLE 7. FLANK WEAR

A - Rake Angle	189.3	3	63.1	3.09 (4.05)
B - Tool Mat'l.	155.3	7	22.2	2.85 (2.17)
A X B	428.7	21	20.4	2.62 (1.74)
Error	498.4	64	7.8	
Total	1271.7	95	13.4	

TABLE 8. CRATER AREA

A - Rake Angle	2.67	3	.89	14.83 (3.07)
B - Tool Mat'l.	1.98	7	.28	4.91 (2.17)
A X B	1.35	21	.06	1.12 (1.74)
Error	3.69	64	.06	
Total	9.69	95	.10	

Values given in ( ) are critical F ratios.

ANOVA TABLES FOR DEPENDENT VARIABLES

TABLE 9. VERTICAL FORCE

Effect	Sum of Squares	df	Mean Square	F - ratio
A - Rake Angle	8089.4	3	2696.4	13.22 (3.07)
B - Tool Mat'l.	1035.2	7	147.9	1.50 (2.17)
A X B	4281.4	21	203.9	2.07 (1.74)
Error	6313.3	64	986.4	
Total	19719.2	95	207.6	

TABLE 10. HORIZONTAL FORCE

A - Rake Angle	19569.7	3	6523.2	14.80 (3.69)
B - Tool Mat'l.	4386.5	7	626.6	2.86 (2.17)
A X B	9251.9	21	440.6	1.99 (1.74)
Error	14164.7	64	221.3	
Total	47372.7	95	498.7	

implies a 5% chance of a test showing significance when none exists. There is also a risk that an F-test will not show significant effects when they do exist however. It is felt that this is the case in the flank wear analysis. Perhaps there were not enough observations available to show significance, or the main effect (rake angle) mean square was negatively biased by the significant interaction mean square producing a lower (and non-significant) main effect F-ratio. In any event, the effect of rake angle on flank wear will be assumed to be significant for the rest of the analysis.

Interaction (rake angle X tool material) terms were significant for all variables except crater area, indicating that some combinations of tool material and rake angle produced results that were quite different from the norm and probably biasing the main effect mean squares and F-ratios. Significant interaction terms require that the data be examined more carefully so that main effects may be evaluated in the absence of interaction.

Extreme examples of this interaction effect can be seen in Figure 10, which shows average tool life as a function of rake angle for each of the test materials.

Single Factor Effects

In order to gain a clearer understanding of how changes in radical negative rake angle and tool material affected the results, one-way ANOVAs were run for each factor at each level of the other factor. For example, ANOVAs were run on tool material at each of the four levels of rake angle. Also, ANOVAs were run on rake angle for each of the eight different tool materials.

This treatment yielded information that allowed a more thorough examination of the results, than was possible using only the two-way analysis.

Rake Angle

The results of analyses showing the effect of changes in radical negative rake angle on the machining results are given in Table 11, and shown graphically for tool life in Figure 10.

Increasing average tool life with increasing radical negative rake angle is the general trend evident in Figure 10. With the exception of the Ford 1½ % Mo tool material, which exhibits no definable tool life trend, all tool materials showed positive responses to an increased radical negative rake angle.

F-tests that were performed on each tool material showed a significant rake angle effect on tool life for the O-30, O-30 HP, and Degussit tool materials only. The lack of statistically significant results for the other five tool materials is not hard to understand in the case of the Ford 1½ % Mo and CCT-707 tool materials, since they did not yield consistent tool life behavior with respect to rake angle. The 5% Cr_2O_3, VR-97, and CO6 tool materials displayed generally increasing values of

TABLE 11. MEAN VALUES BY RAKE ANGLE

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
5% Cr_2O_3					
-5^o	22.3	16.9	1.98	175.7	137.3
-10^o	21.0	12.0	2.05	159.7	116.7
-15^o	26.3	15.3	2.20	172.3	131.7
-25^o	28.3	16.7	2.22	201.7	170.0
Average	24.5	15.2	2.11	177.3	138.9
F-ratio	.83	2.32	.57	7.79	5.76
VR - 97					
-5^o	18.3	11.5	1.99	166.7	105.7
-10^o	19.7	13.7	2.13	182.7	129.0
-15^o	29.0	16.1	2.43	173.3	125.0
-25^o	35.7	20.8	2.33	214.0	174.0
Average	25.7	15.5	2.22	184.2	133.4
F-ratio	1.40	4.13	.79	3.52	4.63
O - 30					
-5^o	12.3	10.3	1.83	165.3	109.0
-10^o	17.7	10.7	2.07	170.3	95.7
-15^o	37.0	15.7	2.42	180.7	126.0
-25^o	40.3	17.6	2.47	196.7	153.3
Average	26.8	13.6	2.20	178.2	121.0
F-ratio	10.54	3.38	4.85	8.08	15.45

The critical F value for all comparisons is 4.07

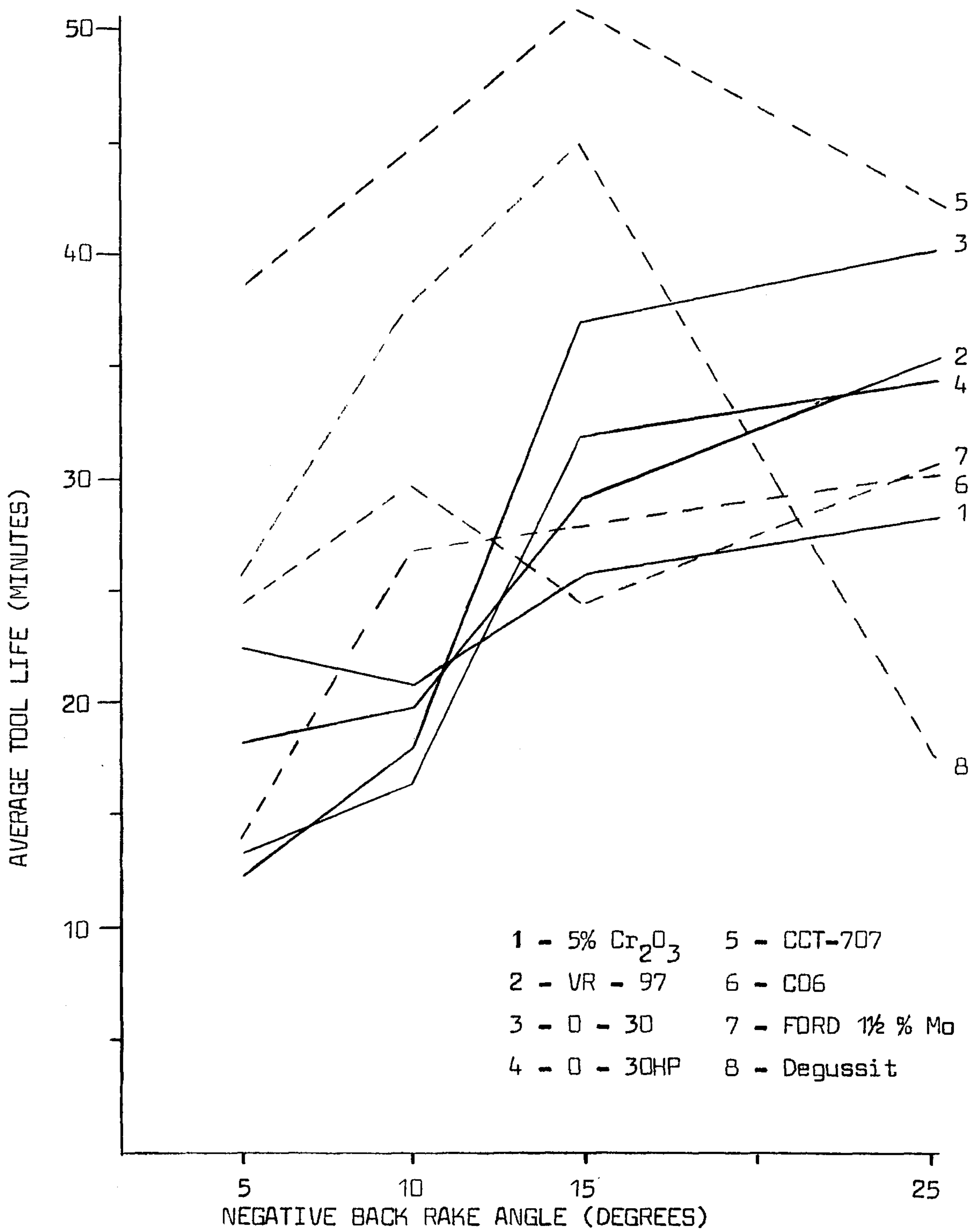
TABLE 11. cont.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
<u>0 - 30 HP</u>					
-5^o	13.0	10.1	1.96	163.7	113.7
-10^o	16.3	10.5	2.08	159.0	99.0
-15^o	31.7	15.4	2.48	182.3	139.7
-25^o	34.3	16.3	2.44	186.7	140.0
Average	23.8	13.1	2.24	172.9	123.1
F-ratio	8.85	4.61	3.57	3.96	2.60
<u>CCT-707</u>					
-5^o	38.3	15.1	2.45	175.7	111.3
-10^o	44.3	18.2	2.55	178.3	125.7
-15^o	51.0	17.0	2.55	184.0	130.7
-25^o	42.3	17.4	2.61	186.7	147.3
Average	44.0	16.9	2.54	181.2	128.7
F-ratio	.64	.78	.37	2.76	10.41
<u>C06</u>					
-5^o	13.7	8.8	1.89	169.3	106.0
-10^o	27.0	13.4	2.38	180.0	116.7
-15^o	28.3	14.0	2.42	181.7	113.3
-25^o	30.3	15.7	2.46	197.0	146.7
Average	24.8	13.0	2.29	182.0	120.7
F-ratio	3.66	4.31	9.53	31.37	7.89

TABLE 11. cont.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
Ford 1½					
-5^o	24.3	12.4	2.17	168.0	107.0
-10^o	29.7	17.2	2.37	176.3	132.3
-15^o	23.7	12.2	2.22	174.7	114.0
-25^o	31.0	15.0	2.43	190.0	143.3
Average	27.2	14.2	2.30	177.2	124.2
F-ratio	.68	1.57	1.84	13.0	5.60
Degussit					
-5^o	25.7	15.1	2.00	174.0	114.7
-10^o	37.7	15.3	2.74	177.7	114.0
-15^o	45.0	17.2	2.85	180.7	120.7
-25^o	17.7	10.4	2.51	177.0	121.0
Average	31.5	14.5	2.52	177.3	117.6
F-ratio	16.51	9.91	10.98	.94	1.11

FIGURE 10. AVERAGE TOOL LIFE AS A FUNCTION OF RADICAL NEGATIVE RAKE ANGLE



of average tool life with increasing radical negative rake angle, yet their tool life results were not statistically significant. This is probably the result of the scatter present within the replications. Tool life variation within replicates would increase the error variance (the denominator of the F-ratio) thus reducing the rake angle effect as measured by an F-test.

Examples of the tool material - rake angle interactions referred to previously can be observed for the Degussit and CCT-707 tool materials in Figure 10. Both materials performed extremely well at all back rake angles up to and including -15^{o}, where they attained maximum average tool life values that were substantially higher than those observed for any of the other six test materials at either -15^{o} or -25^{o}. Reductions in average tool life occurred for both materials at -25^{o} back rake angle however, with the Degussit tool sustaining more than a 60% drop, from 45 to 17.6 minutes.

Rake angle significantly affected the flank wear of the VR-97, O-30 HP, CO6, and Degussit tool materials. Flank wear displayed the same trend as tool life for these four materials, that is, increasing with increasing radical negative rake angle. An exception occurred, as with tool life, for the Degussit tool, which displayed decreased flank wear for -25^{o} as compared to the -15^{o} back rake angle.

It should be observed that the 5% Cr_2O_3 tool material recorded its highest average flank wear at the -5^{o} back rake angle, which is equivalent to a standard SNG insert geometry. It was stated previously that the 5% Cr_2O_3 tool was judged to be a relatively poor performer in a field of 15 ceramic inserts that were examined in a previous study.

In this analysis however, the 5% Cr_2O_3 tool performs equal to and in some instances better than the seven other tools in the study, especially at the more negative rake angles. It would seem that in the case of the 5% Cr_2O_3 tool material, the use of radical negative rake angles has compensated for some deficiencies that existed in the material.

Rake angle significantly affected the crater area of the O-30, CO6 and Degussit tool materials. Again, these materials were the ones displaying crater area trends that paralleled tool life trends with respect to negative rake angles, including the Degussit exception at -25°.

The vertical component of machining force was significantly affected by rake angle for the 5% Cr_2O_3, O-30, CO6, and Ford 1½ % Mo tool materials. The horizontal component was significantly affected for all tool materials except the O-30 HP and Degussit.

Increased machining forces is the area where the penalty is paid for increased tool life via negative rake angles. From Table 5, the average vertical force increase for all eight tool materials in going from -5° to -25° is 23.9 pounds or approximately

14%. For the horizontal force, the average increase is 36.4 pounds or 32%.

Computing the power required for a turning operation as

$$HP = \frac{F_V \times V}{33000} \qquad 18.$$

the average increase that would be required in going from -5° rake angle to -25° would be about 1/2 of a horsepower, from 3.86 to 4.40 HP. In terms of unit horsepower, the increase would be from 1.429 to 1.629 hp/in^3/minute.

For any production facility equipped to fully utilize the potential of ceramic inserts, this meager increase in power should not serve to offset the gains in tool life that are possible with radical negative rake angle use.

A general observation that should be made at this point in the analysis, is that the tool life observed for these ceramic cutting tools does not seem to be strictly wear dependent. In those tool materials showing significant changes in tool wear with rake angle, the average tool wear followed the same pattern as did average tool life values, even for those materials exhibiting a "saw-toothed" tool life - rake angle relation, such as the Ford 1½ % Mo, 5% Cr_2O_3, CCT-707, and Degussit.

The widely accepted notion of tool wear proceeding to a given level, beyond which the tool is failed does not seem to apply in the case of radical negative rake angle tools. Longer tool life was accompanied by higher levels of flank and crater wear, with no degrading effects to the workpiece surface finish.

Tool Material

Results from the analyses to determine the effect of tool material on the values of the dependent variables are given in Table 12.

Examination of Table 12 shows that at three of the four radical negative rake angles, tool material's effect on tool life was judged significant by an F-test. It is felt that this is due to the excellent performance of the CCT-707 and Degussit tool materials up to and including the -15^{0} back rake angle.

Flank wear was judged statistically different by tool material at the -5^{0} and -25^{0} back rake angles.

Crater area was unaffected by tool material at all four rake angles.

Vertical and horizontal forces were affected by tool material only at the -25^{0} back rake angle.

For the purpose of comparing the performance of one rake angle against another, it was necessary to find a homogeneous group of tool materials for which machining variable mean values could be computed and tested. As it is used here, the term homogeneous implies that at each negative rake angle the group of tool materials selected is judged not to be significantly different by an F-test, for the machining variable under consid-

TABLE 12. MEAN VALUES BY TOOL MATERIAL

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Area ($X2500in^2$)	F_V (lb)	F_H (lb)	
-5^0						
5% Cr_2O_3	22.3	16.9	1.98	175.7	137.3	
VR - 97	18.3	11.5	1.99	166.7	105.7	
O - 30	12.3	10.3	1.83	165.3	109.0	
O - 30HP	13.0	10.1	1.96	163.7	113.7	
CCT-707	38.3	15.1	2.45	175.7	111.3	
CO6	13.7	8.8	1.89	169.3	106.0	
Ford 1½	24.3	12.4	2.17	168.0	107.0	
Degussit	25.7	15.1	2.00	174.0	114.7	
Average	21.0	12.5	2.03	169.8	113.1	
F-ratio	3.88	5.59	1.86	1.47	1.51	(2.67)
Average	17.3	11.7	1.97	168.1	113.1	
F-ratio	1.55	4.53	.59	.98	1.63	(3.11)

TABLE 12. cont.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Area ($X2500in^2$)	F_V (lb)	F_H (lb)	
-10^0						
5% Cr_2O_3	21.0	12.0	2.05	159.7	116.7	
VR - 97	19.7	13.7	2.13	182.7	129.0	
O - 30	17.7	10.7	2.07	170.3	95.7	
O - 30 HP	16.3	10.5	2.08	159.0	99.0	
CCT-707	44.3	18.2	2.55	178.3	125.7	
CO6	27.0	13.4	2.38	180.0	116.7	
Ford 1½	29.7	17.2	2.37	176.3	132.3	
Degussit	37.7	15.3	2.74	177.7	114.0	
Average	26.7	13.9	2.30	173.0	116.1	
F-ratio	5.59	2.40	2.61	1.52	2.50	(2.67)
Average	21.9	12.9	2.18	171.3	114.9	
F-ratio	1.80	1.63	.83	1.47	2.60	(3.11)

TABLE 12. cont.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Area ($X2500in^2$)	F_V (lb)	F_H (lb)	
<u>-15^o</u>						
5% Cr_2O_3	26.3	15.3	2.20	172.3	131.7	
VR - 97	29.0	16.1	2.43	173.3	125.0	
O - 30	37.0	15.7	2.42	180.7	126.0	
O - 30 HP	31.7	15.4	2.48	182.3	139.7	
CCT-707	51.0	17.0	2.55	184.0	130.7	
CO6	28.3	14.0	2.42	181.7	113.3	
Ford 1½	23.7	12.2	2.22	174.7	114.0	
Degussit	45.0	17.2	2.85	180.7	120.7	
Average	34.0	15.4	2.45	178.7	125.1	
F-ratio	2.61	1.20	2.30	1.07	1.01	(2.67)
Average	29.3	14.8	2.36	177.5	124.9	
F-ratio	.50	.83	.72	.92	1.06	(3.11)

TABLE 12. cont.

	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Area ($X2500in^2$)	F_V (lb)	F_H (lb)	
-25^o						
5% Cr_2O_3	28.3	16.7	2.22	201.7	170.0	
VR - 97	35.7	20.8	2.33	214.0	174.0	
O - 30	40.3	17.6	2.47	196.7	153.3	
O - 30 HP	34.3	16.3	2.44	186.7	140.0	
CCT-707	42.3	17.4	2.61	186.7	147.3	
CO6	30.3	15.7	2.46	197.0	146.7	
Ford 1½	31.0	15.0	2.43	190.0	143.3	
Degussit	17.7	10.4	2.51	177.0	121.0	
Average	32.5	16.2	2.43	193.7	149.5	
F-ratio	3.35	2.67	1.04	3.02	3.88	(2.67)
Average	33.3	17.0	2.39	197.7	154.6	
F-ratio	1.83	1.16	.65	1.75	2.16	(3.11)

eration. That is, the tools in the homogeneous group can be considered to be from the same population of material, so that the group mean values for a particular dependent variable can be considered to be representative measures of performance for the group at the four radical negative rake angles.

Considering tool life, it is seen that excluding the CCT-707 and Degussit materials which reached their tool life peaks at -15°, the tools in this study exhibited a generally increasing average tool life with increasing radical negative rake angle. Since the CCT-707 and Degussit were different from the other six test materials, as judged by tool life behavior, they were dropped out and analyses were run on tool material at each rake angle and for the five dependent machining variables. The results of this second set of analyses are given as the second set of average and F-ratio values in Table 12.

As can be seen from Table 12, eliminating the Degussit and CCT-707 materials left a group of six tool materials that was homogeneous for every machining variable - rake angle combination except flank wear at -5°.

Referencing Table 12 once again, the reason for this appears to be that the 5% Cr_2O_3 tool material recorded a very high value of average flank wear at this particular angle. In fact it was the highest value of average flank wear recorded by this material at any of the four rake angles. Recalling that the 5% Cr_2O_3 tool material was a relatively poor performer at this standard geometry and also, that as a truly experimental tool material it may be subject to some inconsistent performance, it was also dropped out of the analysis, for this particular machining variable - rake angle combination only, leaving a homogeneous group of five tool materials. It is felt that the five remaining tool materials give a more accurate characterization of flank wear at the -5^{o} back rake angle without biasing the results.

For the homogeneous group of five materials;

Average flank wear (at -5^{o}) = 10.63 ($X10^{-3}$in)

F-ratio = 1.04 (3.48)

The requirements for a homogeneous group of tool materials differed with the dependent machining variable under consideration. As was just mentioned the Degussit and CCT-707 tool materials had to be eliminated in order to achieve homogeneity for tool life and flank wear. Crater area was homogeneous for the group of all eight materials, while vertical and horizontal force needed only the Degussit material removed for homogeneity.

In those cases where more than one homogeneous group of tool materials existed for a dependent variable, duplicate analyses were performed for each group. The homogeneous group that excluded the Degussit and CCT-707 materials was examined for all five dependent machining variables, to maintain consistency.

Average and F-ratio values from the force analysis for the homogeneous group excluding only the Degussit material are given below.

		-5^0	-10^0	-15^0	-25^0	
F_V	Average	169.2	172.3	178.4	196.1	
	F-ratio	1.37	1.53	1.10	2.01	(2.64)
F_H	Average	112.9	116.4	125.8	153.5	
	F-ratio	1.58	2.55	1.05	2.12	(2.64)

Analysis has shown that while the CCT-707 and Degussit tool materials did not belong to the group of six other materials from a tool life standpoint, neither did they form their own homogeneous group of two. Each material was exclusive of the other and of the group of six other test materials.

Analysis of Mean Values

Mean values of the five dependent machining variables for the homogeneous data groupings in Table 12 were analyzed further using the Duncan Multiple Range (DMR) technique. This technique is explained in Appendix E and was used to determine where differences existed within a group of dependent variable mean values that were judged to be significantly different by an F-test.

Values of the error mean square and range factors for testing the five dependent machining variables are given in Table 13.

Analysis will continue by dependent variable.

TABLE 13. DMR TEST INFORMATION

Data Group	Dependent Variable	Error Mean Square	Range Factor
1	Tool Life	66.5	7.17 minutes
1	Flank Wear	10.8	2.89 ($X10^{-3}$in)
1	Crater Area	.059	.212 ($X2500in^2$)
1	Vertical Force	138.5	10.3 lbs.
1	Horizontal Force	347.0	16.4 lbs.
2	Crater Area	.076	.208 ($X2500in^2$)
3	Vertical Force	129.2	9.2 lbs.
3	Horizontal Force	307.9	14.3 lbs.

Data Group 1; Six tool materials, Degussit and CCT-707 excluded

$g = 4,\ m = 18,\ v = 68,\ q_{4,68,.95} = 3.73$*

Data Group 2: Eight tool materials

$g = 4,\ m = 24,\ v = 92,\ q_{4,92,.95} = 3.71$*

Data Group 3: Seven tool materials, Degussit excluded

$g = 4,\ m = 21,\ v = 80,\ q_{4,80,.95} = 3.72$*

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* Table D2, Appendix II, A.J. Duncan, Quality Control and Industrial Statistics, 4th edition, Richard D. Irwin, Homewood ,Ill., 1974.

Tool life

The mean values of tool life that characterize the homogeneous group of tool materials at each of the four radical negative rake angles are given in Figure 11.

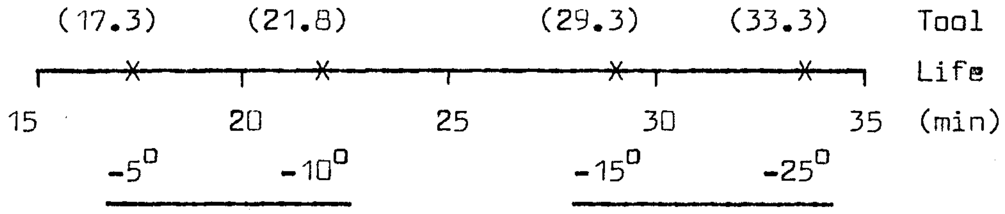


FIGURE 11. DMR CHART FOR TOOL LIFE

The lines under the radical negative rake angle points signify groups of mean values that cannot be said to be statistically different, as determined by the DMR test. Statistically the mean values belonging to any underlined group can be said to be from the same population. Alternatively, it can be said that the differences existing between mean values within any underlined group are due to chance causes (experimental error) rather than some causal system.

Tool life mean values for the four rake angles can be separated into two groups. In the low tool life group, the -5° and -10° tools can be treated statistically as one tool.

The high tool life group, composed of the -15° and -25° tools, yielded statistically greater tool life than the other group.

It would seem that at least a 10° angle ground on the tool (-15° total negative rake angle) is required before substantial tool life improvements are realized for the group of materials. Grinding a 20° angle on the tool (-25° total negative rake angle) appears to give no tool life improvement over the -15° radical negative rake angle.

<u>Flank wear</u>

Flank wear mean values characterizing the homogeneous group of materials at each of the four negative rake angles are given in Figure 12.

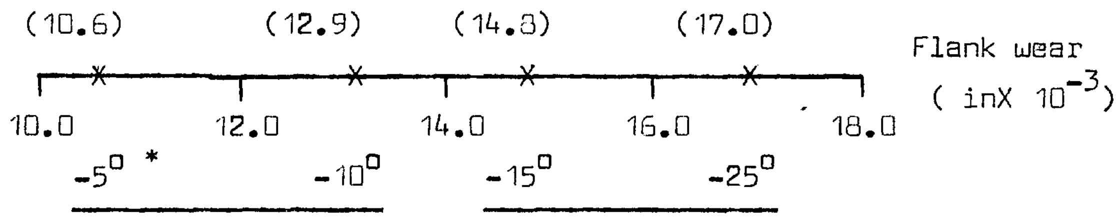


FIGURE 12. DMR CHART FOR FLANK WEAR

Flank wear mean values fell into the same two groupings as did tool life. Some property of the high rake angle tools (-15°, -25°) that is not yet apparent enabled them to last longer and withstand higher flank wear than the low rake angle tools.

<u>Crater area</u>

Crater area mean values characterizing the homogeneous group of six tool materials at each of the four negative rake angles are given in Figure 13.

A similar chart for the homogeneous group including all

* Homogeneous group of five tool materials, 5% Cr_2O_3 dropped

eight tool materials is given in Figure 14.

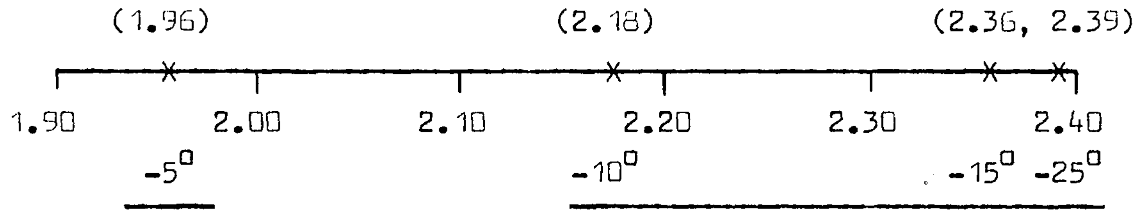


FIGURE 13. DMR CHART FOR CRATER AREA (SIX TOOL MAT'LS)

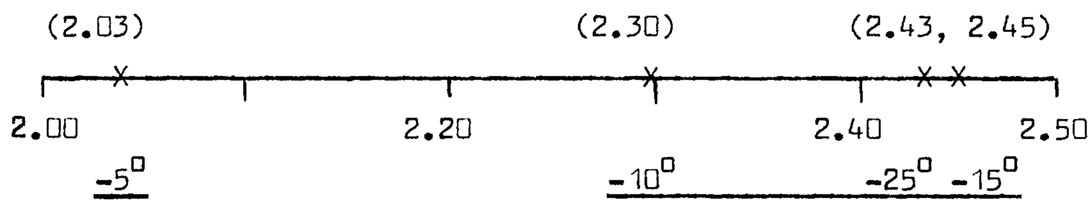


FIGURE 14. DMR CHART FOR CRATER AREA (EIGHT TOOL MAT'LS)

For both of the homogeneous tool material groups tested, crater area broke down into two statistically distinct groups. The high level group contained the -10°, -15°, and -25° tool materials while the low level group consisted only of the -5° tool.

It was not surprising to find that the -15° and -25° tools recorded high values of average crater area, in light of the results obtained for tool life and flank wear. The fact that the -10° tool was also in the high level group is not astounding either, but it does raise a question. Could the grinding of a negative rake angle on the tool affect the observed crater area, through some type of causal system or measurement error? That is, would a -10° radical negative rake angle tool record different values of crater area, than a standard insert held in a -10^0 toolholder?

Answers to the above questions are not obvious at this time. While it is known that negative rake angles increase the compressive loading on a tool tip, it is not known if the radical negative rake angle concept itself produces a loading that would lead to higher crater area than an equivalent geometry with a standard insert.

Vertical force

Vertical (cutting) force mean values characterizing the homogeneous group of six materials at each of the four negative rake angles are given in Figure 15.

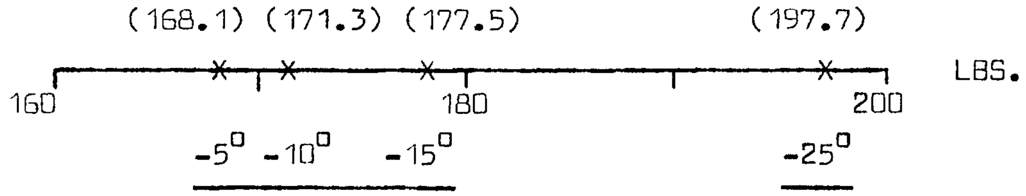


FIGURE 15. DMR CHART FOR VERTICAL FORCE (SIX TOOL MAT'LS)

The equivalent chart for the homogeneous group of seven tool materials is given in Figure 16.

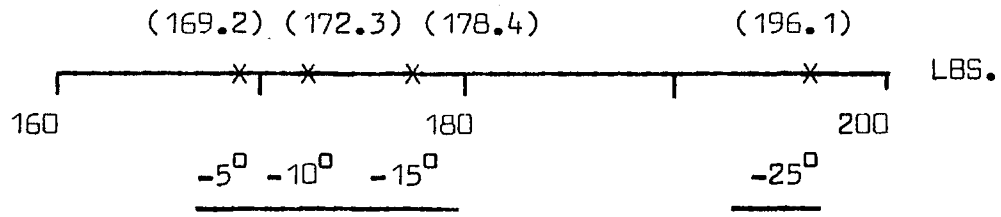


FIGURE 16. DMR CHART FOR VERTICAL FORCE (SEVEN TOOL MAT'LS)

Figures 15 and 16 display some very interesting information. Vertical force mean values are divided into two statistically distinct groups. A low force level group contains the -5°, -10°, and -15° tools while the -25° tool forms the high force level group.

A reversal of trend seems to have occurred. For tool life, flank wear and crater area the -15° tool was always in the high level group, but now it belongs to the low level group. This indicates that radical negative rake angles up to and including -15° do not significantly increase vertical forces (or power required) over that of a standard -5° geometry. It has already been demonstrated that substantial tool life improvements can be gained at -15° and now it would seem that these improvements are possible without increased power requirements.

Horizontal force

Horizontal (thrust) force mean values characterizing the homogeneous group of six materials at each of the four negative rake angles are given in Figure 17.

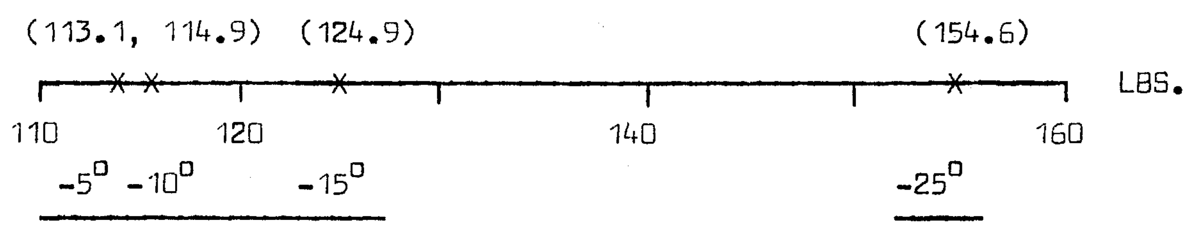


FIGURE 17. DMR CHART FOR HORIZONTAL FORCE (SIX TOOL MAT'LS)

The equivalent chart for the homogeneous group of seven tool materials is given in Figure 18.

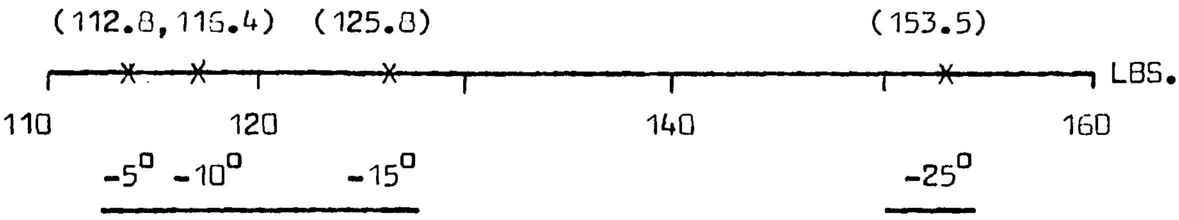


FIGURE 18. DMR CHART FOR HORIZONTAL FORCE (SEVEN TOOL MAT'LS)

Horizontal force exhibited the same low and high force level groups as did vertical force, for both homogeneous tool material groups. It would seem that no penalty is paid from a horizontal force standpoint until a radical negative rake angle of -15^{o} is exceeded.

Summary

Summary of tool performance as measured by the five dependent machining variables will proceed by rake angle. Summary statements made concerning any specific radical negative rake angle apply to the homogeneous group of tool materials for that rake angle - dependent variable combination being tested.

The -5^{o} tool was a standard SNG-433 insert, held in a -5^{o} toolholder. It was in the low level group for all five dependent machining variables examined with the DMR technique.

The -10^{o} tool had a 5^{o} negative rake angle ground on each of four corners, which when combined with the -5^{o} from the tool-holder gave a radical negative rake angle of -10^{o}. This tool was in the low level group for tool life, flank wear, vertical and horizontal force. It was in the high level group for crater area which led to questions concerning how rake angles ground on the tools affected crater wear behavior.

The -15^{o} tool (10^{o} on the tool edge, -5^{o} from the toolholder) was in the high level group for tool life, flank wear and crater area, but in the low level group for both forces. If an optimum geometry had to be picked at this time, I feel that -15^{o} would be a good choice, based on its combination of high tool life and low forces. Also in support of this angle as the optimum geometry would be the excellent tool life shown by the Degussit and CCT-707 tools at this angle.

The -25^{o} tool (20^{o} on the tool edge, -5^{o} from the toolholder) was in the high level group for all five dependent machining variables considered. It recorded mean values of tool life that were statistically the same as those for the -15^{o} tool but the vertical and horizontal forces at this angle were significantly higher. The Degussit and CCT-707 tool materials both exhibited reduced average tool life at -25^{o} as compared to -15^{o}.

Observations on the Performance of Radical Negative Rake Angle Tools

It was felt that large negative rake angles would improve ceramic cutting tool life through increased edge strength resulting from a more compressive loading on the tool tip. Examination of the radical negative rake angle tools at the end of their tool lives using Scanning Electron Microscopy (SEM) was done, in order to determine why various tools performed the way in which they did.

Figures 19a and 19b show a -15^{0} 5% Cr_2O_3 tool and a -10^{0} CCT-707 tool at the end of their tool lives. It should be noted that the CCT-707 tool has a sharp cutting edge (the intersection of the crater and flank wear areas), while the 5% Cr_2O_3 tool has a flat or rounded contour in this area. It is felt that this difference is not so much a function of tool material, but depends largely on the geometry (negative rake angle) of the insert.

It was observed that the use of radical negative rake angles tended to push the crater back from the cutting edge, as shown in Figure 20. This should greatly improve edge strength by reducing edge pressure and the probability of crater break-through. Forces are increased, but as the previous section has shown, appreciable increases did not occur until radical negative rake angles of -25^{0} are reached and even then there was only a 14% increase in vertical force (over -5^{0}).

Increasing radical negative rake angles should also increase edge strength due to a lessened effect of crater wear on the

FIGURE 19. A) OVERALL VIEW, -15° 5% Cr_2O_3, 33 MINUTES

ROUNDED CUTTING EDGE

FIGURE 19. B) OVERALL VIEW, -10° CCT-707, 51 MINUTES

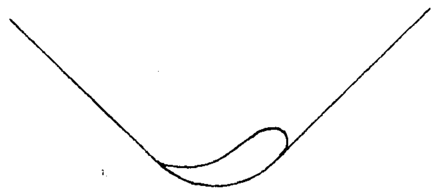
SHARP CUTTING EDGE

included edge angle between the effective back rake angle and the tool flank. This effect is shown in Figure 21.

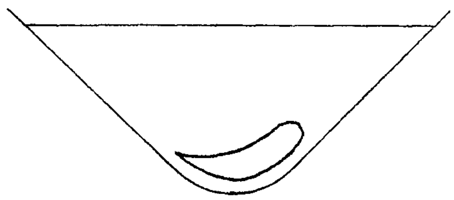
Electron microprobe analysis performed on the tools revealed elemental segregation of iron and manganese in the crater area and on the tool top above the crater for all rake angle - tool material combinations examined. Elemental zinc and sodium were also observed for some of the higher negative rake angle tools, indicating that the highest temperatures were present at these angles. The elemental segregation that occurred is an indication that temperatures on the order of 1000^{o} C were present in the shear zone area during machining.

The high temperatures present in the shear zone area degrade both the tool and workpiece materials. Workpiece degradation is in the form of reduced yield strength in the portion of the chip near the shear zone. Reduced workpiece material yield strength would lead to a reduction in the resultant machining force, due to reduced vertical (cutting) and frictional force components.

The reduction in yield strength for 4340 steel is extremely rapid for temperature increases above 800^{o} F, as shown in Figure 22.[19]. Although no quantitative temperature data is available for the negative rake angle tools, SEM and microprobe analyses indicate that these tools were operating at temperatures substantially higher than 800^{o} F. The temperature increases that accompany increased radical negative rake angles may tend to offset force increases through reduced material yield strength.



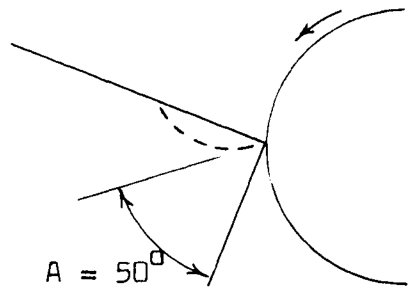
A) STANDARD INSERT



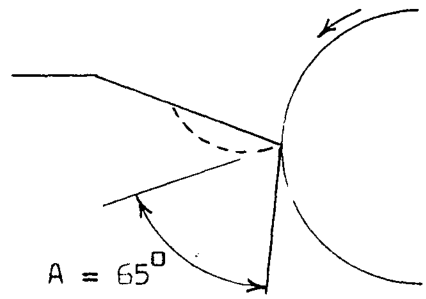
B) RADICAL NEGATIVE RAKE

ANGLE TOOL

FIGURE 20. EFFECT OF RADICAL NEGATIVE RAKE ANGLE ON CRATER



A) STANDARD INSERT



B) RADICAL NEGATIVE RAKE

ANGLE TOOL

FIGURE 21. EFFECT OF CRATER WEAR ON INCLUDED EDGE ANGLE

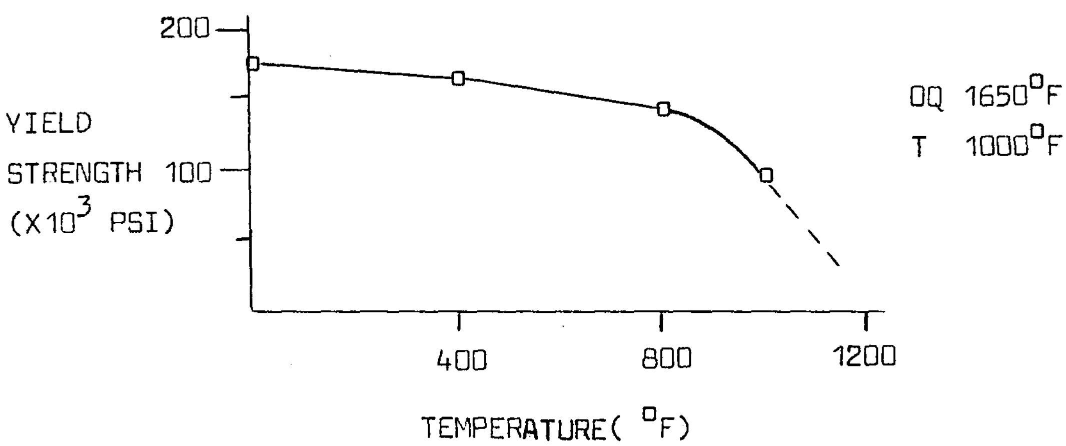


FIGURE 22. YIELD STRENGTH VS. TEMPERATURE FOR 4340 STEEL

Increased negative rake angles tend to moderate the temperature increases that they produce by increasing the shear plane angle and so, the chip thickness. Thicker chips should lower the average shear zone temperature, since they can carry away more heat.[20] Ceramic tools conduct very little heat away from the tool tip, due to their low thermal conductivity, so that most of the heat produced in machining must be carried away by the chips.

SEM revealed cracks in the crater and flank wear areas of these tools. Examples are given in Figure 23.

Crater cracks are thought to be the result of the high compressive loadings on the tool and creep, or other mechanisms of anelastic deformation, resulting from the high temperatures and the heating - cooling cycle imposed every two minutes, as the machining operation was interrupted to take tool wear measurements.

Flank wear land cracks were the result of tensile loads and the heating - cooling cycle.

The first three to five minutes of machining during a test, generally produced tightly curled continuous chips. During advanced stages of wear, chip formation would alternate between tightly curled and long unbroken continuous chips.

Tight chip curl is accompanied by decreased contact length and lower overall forces, but increased stress concentration and temperature, as the resultant force acts closer to the cutting edge.[21] Chip curl decreased and contact length increased as tool

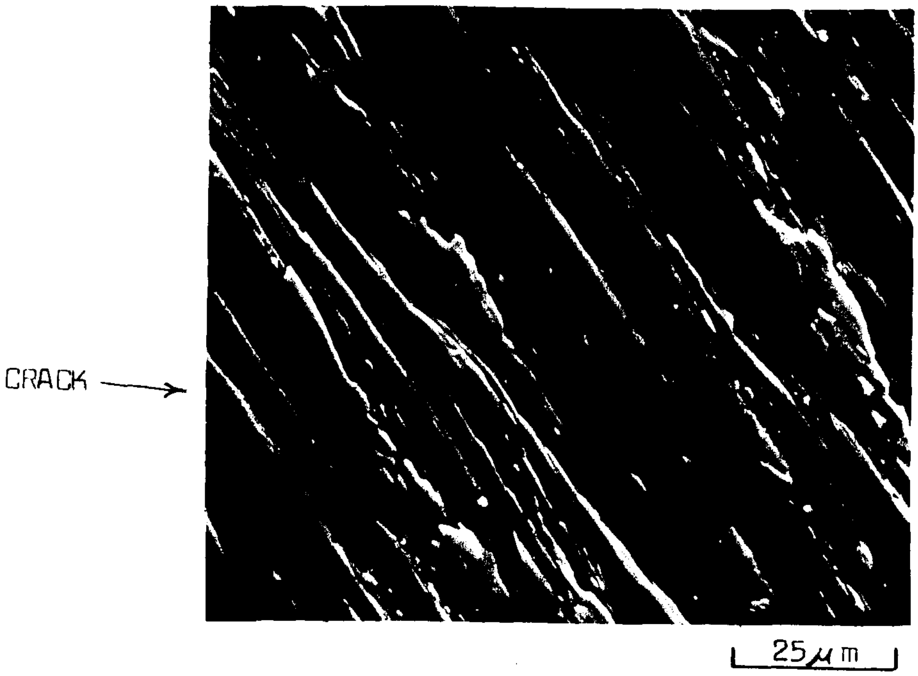


FIGURE 23. A) CRATER AREA, -10° CCT-707, 51 MINUTES

SMALL CRATER CRACK

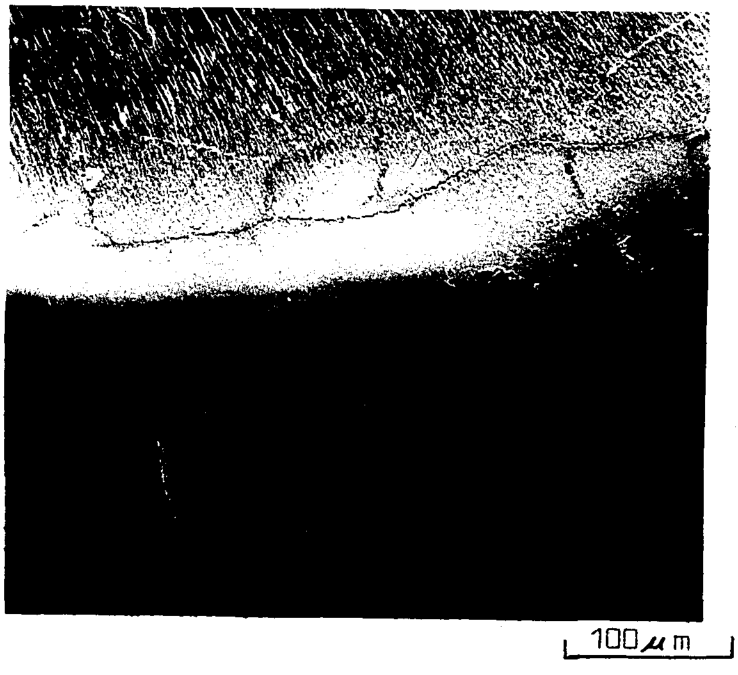


FIGURE 23. B) LEADING EDGE, -25° 5% Cr_2O_3,33 MINUTES

CRATER CRACKS PARALLELING CUTTING EDGE

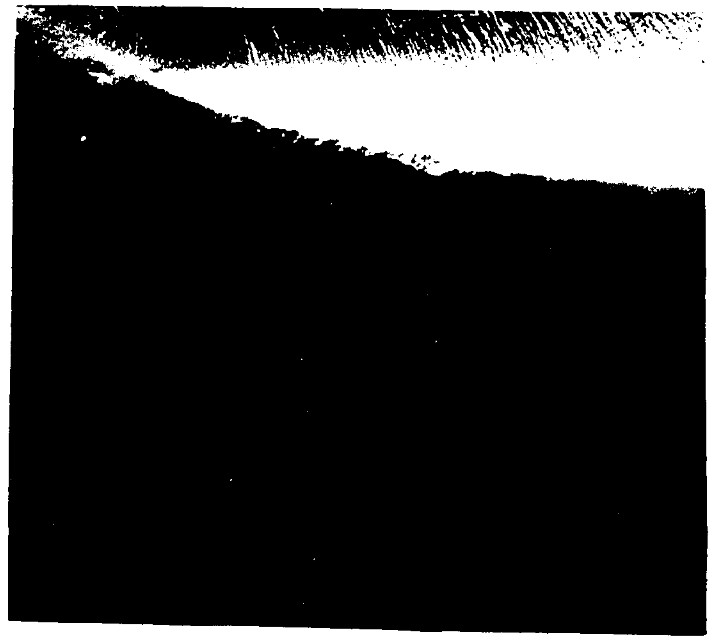


FIGURE 23. C) TRAILING EDGE, -25^{0} 5% Cr_2O_3,33 MINUTES

CRACKS IN THE FLANK WEAR LAND

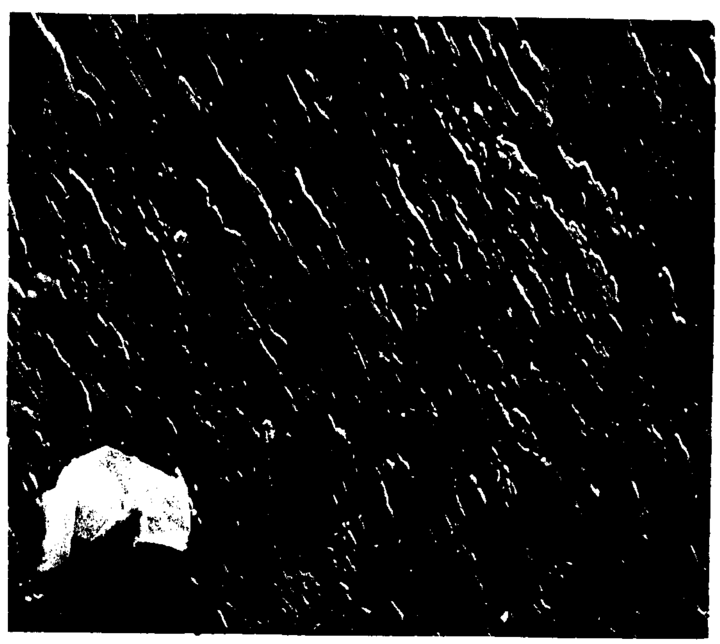


FIGURE 23. D) CRATER AREA, -10^{0} D-30 HP, 13 MINUTES

CRATER AREA CRACK

wear progressed, reshaping the cutting edge so as to minimize stress concentrations.

Alternating chip curl produced force fluctuations that were measured by the dynamometer and displayed on the strain amplifier recorder. Figure 24 displays the magnitude of force fluctuations that were encountered. Variations of 80 pounds for the vertical force component and 35 pounds for the horizontal force component were common. With force variations such as these, it is possible that increased stress levels at the cutting edge during periods of high force would exceed the cyclic fatigue stress limit of the material, leading to the propagation of fatigue cracks.

The three tool materials that performed the best from a tool life standpoint, the Degussit, CCT-707, and 0-30, also had the lowest hardness values of the eight materials tested. (See Table 14) It has been speculated that "soft" tool materials perform well in surface finish critical operations such as those in this analysis since they wear more uniformly than a harder tool material.[22.] SEM of the crater areas of the soft CCT-707 and the hard 0-30 HP materials show the difference in crater wear that was observed for these two materials.

In Figure 23a the wear of the CCT-707 tool is characterized by severe abrasion and plastic flow. Figure 23b shows crater wear for the 0-30 HP that is not nearly as severe. Both tools were considered to have failed by the surface finish criterion, with the 0-30 HP tool recording a tool life that was only 1/3 that of the

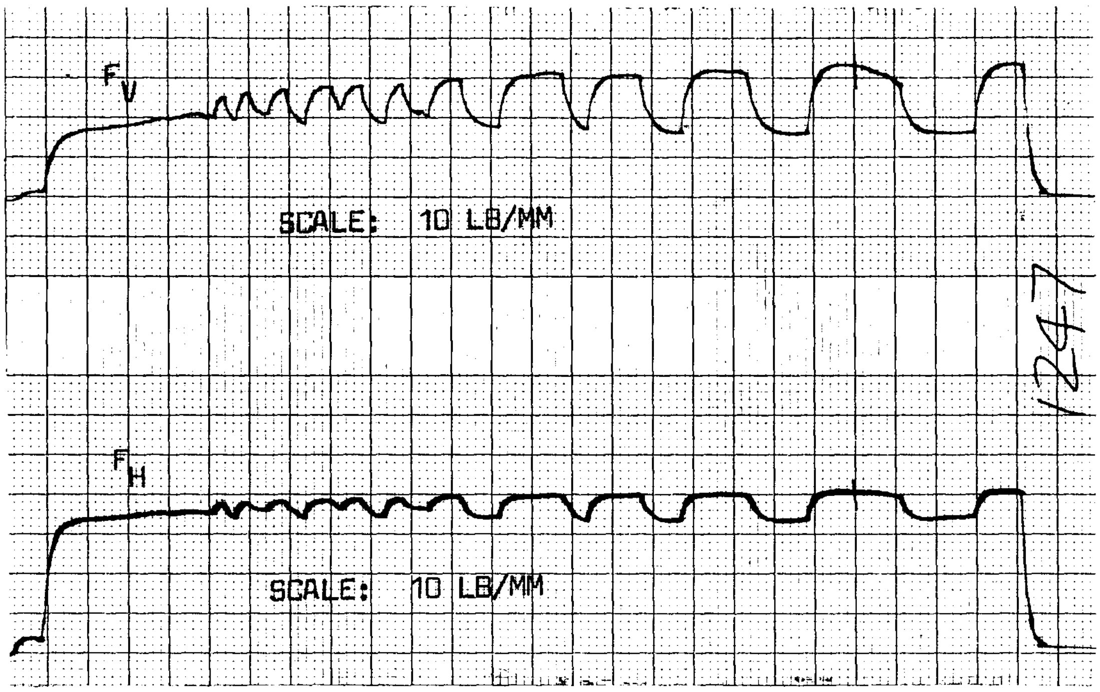


FIGURE 24. FORCE PRINTOUT, FINAL CUT; -15° DEGUSSIT, 41 MIN.

TOOL	HARDNESS(DPH)[1.]	DENSITY[2.]	COMP. STRENGTH[2.]
5% Cr_2O_3	2142	4.03 g/cm^3	$565^{*} \times 10^3$ psi
VR-97	1861	3.97	450
O-30	1742	4.091	505
O-30 HP	2230	4.094	525**
CCT-707	1806	3.93	445
CO6	1969	3.94	650
FORD 1½ % MO	1930	3.99	---
DEGUSSIT	1524	3.88	248

* Based on a modulus of rupture of 102,300 psi (X correction factor)

** Speculated, it is known that the O-30 HP tool is slightly stronger than the standard O-30.

1. Measurements from Materials Research Center, Lehigh University.
2. Values from E. Dow Whitney, Reference 4.

TABLE 14. PHYSICAL PROPERTIES OF TOOL MATERIALS

CCT-707 tool. This would seem to suggest that optimizing tool material properties is not a universal rule for good machining performance. Depending on the particular application, it may be better to let a tool wear, for good surface finish, rather than seeking to minimize flank and crater wear.

In addition to being low in hardness, the Degussit tool material was also of low density (higher porosity), which was reflected by a very low compressive strength. The CCT-707 material was low in density and compressive strength also.

The average tool life values observed for the Degussit and CCT-707 tool materials decreased at the -25^{o} radical negative rake angle. This coincides with the significant increase in vertical force that was observed at this rake angle and the speculation that the highest temperatures occurred at the highest rake angles. The high forces and temperature apparently created conditions at the tool tip that were too severe for these materials to withstand, so that accelerated tool wear and decreased tool life resulted.

Examination of SEM photographs showed no consistent evidence that would explain why a tool recorded a given tool life, other than the condition of the trailing edge. The trailing edge of an insert plays a major role in determining the surface profile left on the workpiece by the tool, in other words the surface finish. Nonuniform wear of the tool edge would tend to increase the observed surface finish readings. The trailing edge of an insert is shown in Figure 25.

Excessive wear, microspalling or edge chipping in the area of the trailing edge can all cause poorer surface finish (more surface roughness). Examples of each are shown in Figure 26.

The O-30 HP tool was the hardest material in the study and the most brittle. In five of the six tests conducted at the -15° and -25° rake angles, tool life was determined by tool fracture when portions of the crater - flank interface failed. The higher hardness may have minimized tool wear, but the higher forces caused brittle fracture to occur.

It is recognized that the grinding of radical negative rake angles (or edge chamfers) on an insert would entail some added cost in production, since it would require additional operations and locating devices. No special finishing was performed on these inserts however, so that no special equipment would be required, only additional operations. Since inserts are individually finished, the marginal increase in cost for these extra operations may not be prohibitive in light of the increases in performance that are possible.

In this analysis, tool life for the homogeneous group of six tool materials increased approximately 100% from the -5° to the -25° rake angle. If a tool seat could be developed that would properly support an insert with negative rake angles ground on all eight corners, then the concept should be economically feasible, since the tool life of an insert would be essentially doubled.

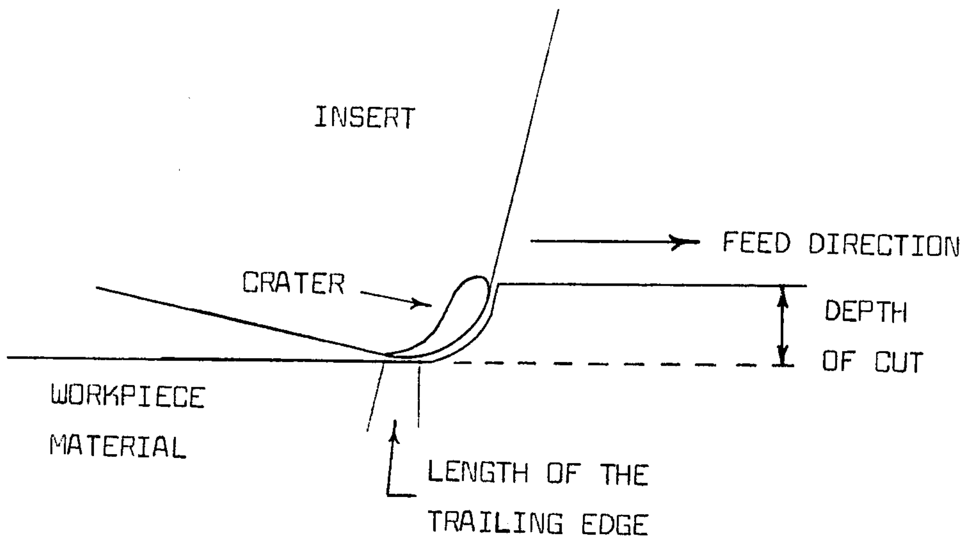


FIGURE 25. THE TRAILING EDGE OF AN INSERT

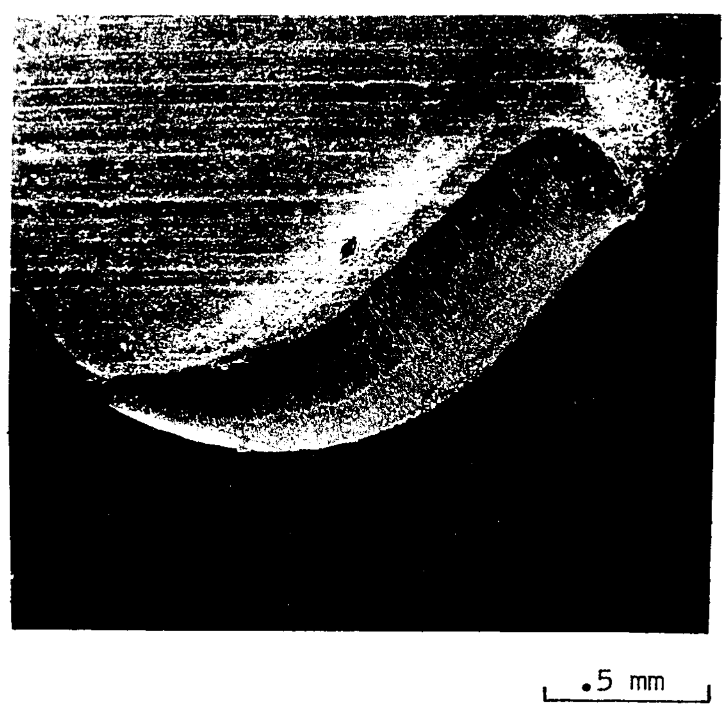


FIGURE 26. A) OVERALL VIEW, -15° 5% Cr_2O_3, 15 MINUTES (1000 SFPM) EDGE CHIPPING

FIGURE 26. B) TRAILING EDGE, -10° CCT-707, 51 MINUTES

UNEVEN FLANK WEAR

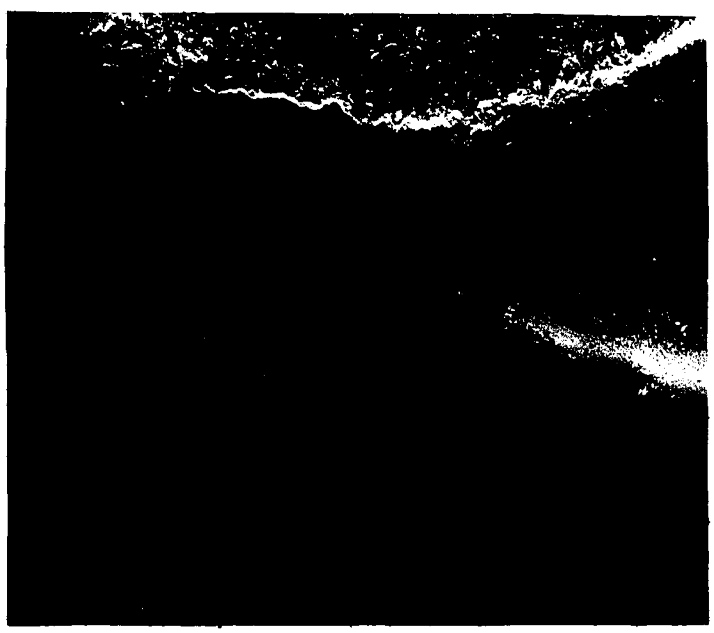


FIGURE 26. C) TRAILING EDGE, -25° 5% Cr_2O_3, 33 MINUTES

UNEVEN FLANK WEAR

CONCLUSIONS

1. The radical negative rake angle edge geometry that was developed, operated successfully in a finish turning operation on Rc 35, 4340 steel. Machining was done at 750 sfpm, .006 ipr and .050 inch depth of cut. More severe conditions (1000 sfpm) led to early fracture failure of the tool and chip control problems.
2. All five dependent machining variables that were measured generally increased with increasing negative rake angle.
3. Of the four radical negative rake angles examined, the -15° rake angle provided the best performance in this application, where tool life was determined by surface finish. The -15° rake angle tool yielded significantly longer tool life than a standard insert (-5° tool) while recording machining forces that were not significantly different.
4. The major beneficial effect of the radical negative rake rake angle concept is that it forces the crater back from the cutting edge and retains a small 5° end relief angle for all negative rake angles, both of which improve edge strength.
5. Significant differences were found among the eight tool materials from a tool life standpoint. The Degussit and CCT-707 tool materials displayed different tool life - rake angle relations than the other six materials. Both achieved maximum average tool life at the -15° rake angle and suffered

reductions in tool life at -25^{o}.

6. "Soft" tool materials yielded better tool life than harder materials, apparently due to their ability to wear uniformly. By resisting grain pullout, edge chipping and other mechanisms that would lead to a nonuniform edge profile these materials produced the best surface finishes for the longest times.

7. Tool life as measured by surface finish is not strictly wear dependent. The magnitude of flank or crater wear present on the tool tip is not as important as the condition of the trailing edge.

8. The wear mechanisms observed to be active on these tools were abrasion, plastic flow and microspalling. Creep and fatigue mechanisms were also thought to be operative, as were various chemical wear mechanisms.

RECOMMENDATIONS FOR FUTURE WORK

The following areas could be pursued by future investigators of ceramic tools.

A. General

1. The correlation of physical properties of the tool material to observed machining performance.
2. An evaluation of the effect of chemical polishing of ceramic inserts on their performance. Also, development of an inexpensive polishing technique if polishing proves to be beneficial.

B. Radical Negative Rake Angle Tools

1. An evaluation of the performance of these tools on materials in the Rc 50-60 range.
2. An evaluation of the performance of these tools relative to tools having a chamfered edge or tumbled radii edge.
3. An evaluation of performance in interrupted cutting and for roughing cuts.

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APPENDIX A

WORKPIECE MATERIAL

Chemical composition of AISI 4340 steel (percent).*

C	.38 - .43	Si	.20 - .35
Mn	.60 - .80	Ni	1.65 - 2.00
P	.020	Cr	.70 - .90
S	.013	Mo	.20 - .30

Heat Number	Hardness Range (Rc)
A - 3	35.5 - 36.5
A - 5	34.5 - 37
BB - 1	33.5 - 36
BB - 2	33 - 35.5

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* Modern Steels and their properties, 7th edition, Handbook 2757, Bethlehem Steel Corporation, Bethlehem, Pa., 1972, p 154.

APPENDIX B

MACHINING DATA - FEASIBILITY PHASE

TOOL MATERIAL	RAKE ANGLE	REP	FLANK WEAR ($X10^{-3}$)	CRATER AREA# (in^2)	TOOL LIFE (min)	F_V (lb)	F_H (lb)
V = 750							
5% Cr_2O_3	-5^o	1	19.0	2.08	27	175	130
		2	17.3	1.81	19	175	155
	-10^o	1	14.6	2.25	23	145	105
		2 *	9.1	1.50	11	166	125
	-15^o	1	16.2	2.22	27	172	135
		2	17.9	2.20	33	180	125
	-25^o	1	18.6	2.27	27	195	155
		2	16.2	2.01	33	190	155
VR - 97	-5^o	1	10.9	1.99	13	165	107
		2	7.5	1.46	7	155	93
	-10^o	1	10.9	1.80	15	163	112
		2	12.8	2.10	15	170	110
	-15^o	1	12.9	2.21	13	170	120
		2	16.4	2.31	29	170	115
	-25^o	1	18.2	2.10	29	200	150
		2	22.7	2.16	39	202	165

* Indicates crater breakthrough as a determinent of tool life.

\# Crater area (in^2 X 2500)

APPENDIX B

MACHINING DATA - FEASIBILITY PHASE

TOOL MATERIAL	RAKE ANGLE	REP	FLANK WEAR $(X10^{-3})$	CRATER AREA# (in^2)	TOOL LIFE (min)	F_V (lb)	F_H (lb)
V = 1000							
5% Cr_2O_3	-5^0	1 *	16.0	1.44	11	160	135
		2 *	18.7	1.69	13	203	250
	-10^0	1 *	14.5	1.96	15	159	100
		2	11.9	2.10	13	155	110
	-15^0	1	13.3	1.94	13	156	107
		2	13.7	2.05	13	157	125
	-25^0	1 *	17.1	1.87	16	190	140
		2	14.8	1.84	13	180	140
VR - 97	-5^0	1	10.2	1.91	9	150	95
		2	11.2	1.95	11	149	98
	-10^0	1	13.8	1.80	13	151	110
		2	11.5	1.50	11	152	118
	-15^0	1	8.7	1.57	11	160	105
		2	14.2	2.05	13	165	120
	-25^0	1	18.0	2.15	19	185	130
		2	No test, edge ruined by chip contact				

\# Crater area $(in^2 \times 2500)$

APPENDIX C

Radical Negative Rake Angle = -5°

Tool Material	Rep	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
5% Cr_2O_3	1	27	19.0	2.08	175	130
	2	19	17.3	1.81	175	155
	3	21	14.5	2.04	177	127
	Avg	22.3	16.9	1.98	175	137
VR - 97	1	13	10.9	1.99	165	107
	2	7	7.5	1.46	155	93
	3	35	16.2	2.51	180	117
	Avg	18.3	11.5	1.99	167	106
O - 30	1	11	11.6	1.63	158	92
	2	15	9.7	2.03	172	130
	3	11	9.7	1.83	166	105
	Avg	12.3	10.3	1.83	164	109
O - 30HP	1	17	12.7	2.18	155	86
	2	13	9.3	1.73	175	142
	3	9	8.4	1.96	161	113
	Avg	13.0	10.1	1.96	164	114
CCT - 707	1	25	14.1	2.15	177	110
	2	41	14.6	2.50	170	109
	3	49	16.7	2.70	180	115
	Avg	38.3	15.1	2.45	176	111
CO6	1	13	10.0	1.95	168	115
	2	15	8.5	1.92	170	95
	3	13	7.9	1.80	170	108
	Avg	13.6	8.8	1.89	169	106
FORD 1½	1	17	12.3	2.02	170	110
	2	25*	13.0	2.19	165	105
	3	31	11.8	2.30	169	106
	Avg	24.3	12.4	2.17	168	107
DEGUSSIT	1	21	13.7	2.00	172	107
	2	27	16.1	1.94	179	120
	3	29	15.5	2.06	171	117
	Avg	25.6	15.1	2.00	174	115

* - Indicates tool life determined by fracture failure

APPENDIX C

Radical Negative Rake Angle = - 10°

Tool Material	Rep	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
5% Cr_2O_3	1	23	14.6	2.25	145	105
	2	11	9.1	1.50	166	125
	3	29	12.4	2.40	168	120
	Avg	21	12.0	2.05	160	117
VR - 97	1	15	10.9	1.80	163	112
	2	15	12.8	2.10	170	110
	3	29	17.5	2.49	215	165
	Avg	19.6	13.7	2.13	183	129
O - 30	1	25	14.4	2.03	180	90
	2	15	8.5	2.18	160	95
	3	13	9.3	2.00	171	102
	Avg	17.6	10.7	2.07	170	96
O - 30HP	1	23	13.3	2.44	167	107
	2	13	8.5	1.72	145	90
	3	13	9.6	2.08	165	100
	Avg	16.3	10.5	2.08	159	99
CCT - 707	1	51	22.0	2.69	175	125
	2	51	18.0	2.46	180	137
	3	31	14.7	2.50	180	115
	Avg	44.3	18.2	2.55	178	126
CO6	1	31	15.5	2.45	185	130
	2	27	12.0	2.35	175	107
	3	23	12.8	2.34	180	113
	Avg	27.0	13.4	2.38	180	117
FORD 1½	1	37*	23.0	2.42	180	150
	2	25	12.4	2.24	169	122
	3	27	16.2	2.45	180	125
	Avg	29.6	17.2	2.37	176	132
DEGUSSIT	1	43	14.5	2.60	173	112
	2	35	15.7	3.08	175	115
	3	35	15.7	2.55	185	115
	Avg	37.6	15.3	2.74	178	114

APPENDIX C

Radical Negative Rake Angle = -15^{o}

Tool Material	Rep	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^{2}$)	F_{V} (lb)	F_{H} (lb)
5% Cr_2O_3	1	27	16.2	2.22	172	135
	2	33	17.9	2.20	180	125
	3	19	11.7	2.19	165	135
	Avg	26.6	15.3	2.20	172	132
VR - 97	1	13	12.9	2.21	170	120
	2	29	16.4	2.31	170	115
	3	45	19.1	2.78	180	140
	Avg	25.6	16.1	2.43	173	125
O - 30	1	25	13.5	2.03	185	130
	2	43	16.1	2.61	182	125
	3	43	17.4	2.63	175	123
	Avg	37.0	15.7	2.42	181	126
O - 30HP	1	35*	17.0	2.34	180	127
	2	39**	16.7	2.65	200	175
	3	21	12.4	2.45	167	117
	Avg	31.7	15.4	2.48	191	140
CCT - 707	1	45	16.0	2.45	190	140
	2	53	17.8	2.54	177	127
	3	55	17.3	2.67	185	125
	Avg	51.0	17.0	2.55	184	131
CO6	1	23	11.3	2.11	183	110
	2	43	17.7	2.64	180	130
	3	19	13.0	2.51	182	100
	Avg	28.3	14.0	2.42	182	113
FORD 1½	1	35	13.7	2.26	177	135
	2	15	9.7	2.00	172	107
	3	21	13.1	2.41	175	100
	Avg	23.7	12.2	2.22	175	114
DEGUSSIT	1	53	19.4	2.72	180	126
	2	41	18.1	3.12	185	127
	3	41	14.2	2.70	177	109
	Avg	45.0	17.2	2.85	181	121

** - Indicates crater fracture, but tool continued to generate acceptable surface finish.

APPENDIX C

Radical Negative Rake Angle = - 25°

Tool Material	Rep	Tool Life (min)	Flank Wear ($X10^{-3}$in)	Crater Wear ($X2500in^2$)	F_V (lb)	F_H (lb)
5% Cr_2O_3	1	27	18.6	2.27	195	155
	2	33	16.2	2.01	190	155
	3	25	15.2	2.37	220	200
	Avg	28.3	16.7	2.22	202	170
VR - 97	1	29	18.2	2.10	200	150
	2	39	22.7	2.16	202	165
	3	39	21.5	2.73	240	207
	Avg	35.7	20.8	2.33	214	174
O - 30	1	31*	12.3	2.20	205	155
	2	45	17.1	2.50	185	145
	3	45	23.4	2.70	200	160
	Avg	40.3	17.6	2.47	197	153
O - 30HP	1	33*	13.2	2.30	190	135
	2	31*	16.5	2.42	180	135
	3	39*	19.1	2.60	190	150
	Avg	34.3	16.3	2.44	187	140
CCT - 707	1	37	15.9	2.44	180	140
	2	31	15.2	2.55	190	147
	3	59	21.0	2.85	190	155
	Avg	42.3	17.4	2.61	187	147
CO6	1	29	13.0	2.43	196	145
	2	33	15.2	2.52	193	145
	3	29	18.8	2.42	202	150
	Avg	30.3	15.7	2.46	197	147
FORD 1½	1	23	11.4	2.29	190	140
	2	35	17.1	2.58	185	145
	3	35	16.4	2.42	195	145
	Avg	31.0	15.0	2.43	190	143
DEGUSSIT	1	23	11.2	2.39	180	120
	2	15	9.4	2.56	179	121
	3	15	10.6	2.57	172	122
	Avg	17.7	10.4	2.51	177	121

APPENDIX D

Analysis of Variance

"One of the most powerful tools of statistical analysis is what is known as analysis of variance. Basically it consists of classifying and cross-slassifying statistical results and testing whether the means of a specified classification differ significantly. In this way it is determined whether the given classification is important in affecting the results." *

For the two factor experimental design in this anlaysis, the theoretical model underlying the analysis assumes the following, for each dependent variable examined:

1. An overall mean μ for each variable
2. A row effect (tool material bias) T_i, $(i= 1,\ldots,8)$
3. A column effect (rake angle bias) Q_j, $(j=1,2,3,4)$
4. An interaction effect (tool material - rake angle joint bias) B_{ij}, and
5. A random residual (experimental error) E_{ijk}, which is normally distributed with zero mean and standard deviation σ, $(k=1,2,3)$

with possibly any of the effects 2,3,4 all being zero. k is the number of replicates.

Using this model, the observed value of any of the dependent variables would have the form

$$X_{ijk} = \mu + T_i + Q_j + B_{ij} + E_{ijk}$$

The analysis of variance technique seeks to determine whether the row, column and interaction effects produce significant changes in the observed values of X_{ijk}. This is accomplished as follows.

1. Mean values are calculated for each possible source of variation (factors in the experiment)
2. A measure of the variation of the data values about these mean values is obtained by computing the sum of the squared deviations between mean values and observed values.
3. Mean squares (MS) are computed for each factor as the quotient of the sum of squares (SS) over the degrees of freedom (df = number of levels for the factor - 1)

$$MS_A = \frac{SS_A}{df_A} \qquad \text{(for factor A)}$$

4. An estimate of experimental error is found by summing the squared differences between replicates and the replicate mean for all cells and dividing the total by the error degrees of freedom.

$$MS_E = \frac{SS_E}{df_E}$$

5. The ratio of factor mean squares to error mean squares gives an F-ratio for each factor

$$F_A = \frac{MS_A}{MS_E}$$

If the F-ratio is large, it indicates that the effect of the factor on the dependent variable is significant relative to random error. F-ratios are compared to critical values of the F-statistic to determine significance. Critical values of the F-statistic are given as required in this analysis.

A mixed model ANOVA was used for evaluation in this study. Rake angle was taken to be a fixed effect.

Tool material was a random effect, since the tool materials chosen were meant to be a sample of the population of ceramic tool materials that were available.

With this model, F-ratios for the random and interaction effects are computed as described previously. The F-ratio of the fixed effect is computed as

$$F_F = \frac{MS_F}{MS_I}$$

where MS_I is the interaction mean square.

The approximate F-test procedure, with adjusted degrees of freedom, that was worked out by J.P. Imhoff has been used.**

* A.J. Duncan, Quality Control and Industrial Statistics, 4th edition, Richard D. Irwin, Inc, Homewood, Ill., 1974, p.609.

** Annals of Mathematical Statistics, Vol XXXIII (1962) pp. 1085 - 1094.

Using this technique, the F-statistic of the fixed effect that was computed as above, is compared to a value of $F_{m,mh}$ that is given in Table K, Appendix II of Duncan.

$$m = J-1 \qquad h = (I-1)(1 + (I-2)(1-\theta)^2)^{-1}$$

and

J = number of levels of the random factor

I = number of levels of the fixed factor

$$\theta = \min \begin{bmatrix} 1 \\ {}^{MS_E}/_{MS_I} \end{bmatrix}$$

APPENDIX E

Duncan Multiple Range Technique

The Duncan Multiple Range technique is a method of analyzing a group of mean values that have been shown to be significantly different by an F-test or a studentized range test. The analysis is aimed at determining where within a group of means the difference exists.

The test procedure, by way of example is quoted from Duncan.*

" If a group of g means are shown to be significant by an F-test or studentized range test, it may be of interest to analyze the group further. If we divide the g means into g subgroups containing g-1 means each, we may wish to determine whether the means of each subgroup differ significantly. To do this we can apply further F or range tests to each subgroup. If a subgroup shows no significant difference, the analysis of that group stops. If a significant diffenence is found, then such subgroups can be further subdivided. The general rule will be that the means of no subgroup will be declared significantly different unless the means of all larger groups containing this particular subgroup are significantly different. Ultimately the analysis will yield a

* A.J. Duncan, Quality Control and Industrial Statistics, 4th edition, Richard D. Irwin, Inc., Homewood, Ill., 1974, pp. 703 - 705.

partial ranking of the means of the set.

It will be noted that the number of different subgroups of size g-1, g-2, and so on, that can be made from g means rises rapidly as g increases. Thus some orderly procedure is necessary. The usual approach is to arrange the g means in order of size and then, working first from one end and then the other, to consider subgroups of g-1 and 1, g-2 and 2, and so forth. If at any time a test of a subgroup indicates no significant difference, then the analysis stops for that subgroup.

As an example, let us analyze the following set of 6 means:

A = 502	D = 498
B = 528	E = 600
C = 564	F = 470

These are taken from a 5X6 one-way analysis of variance for which the error mean square, based on 24 degrees of freedom is equal to 2451. The studentized-range coefficient for g = 6, v = 24 is 4.37 (see Table D2, Appendix II), and the range factor for testing the above set of means is $4.37\left(\frac{2451}{5}\right)^{1/2} = 96.7$. The range of the 6 means in question is 600 - 470 = 130 which is greater than 96.7, so we conclude that the 6 means differ significantly.

Arranged in order of size we have

F	D	A	B	C	E
470	498	502	528	564	600

From the previous analysis we conclude that F is less than E. Next look at the subgroup F, D, A, B, and C. For the moment let us be ultraconservative regarding the Type I error (with resultant loss in Type II error) and let us use the studentized-range allownace for the whole set of g means to sepatate significantly different means in subgroups containing less than g means. We shall call this the Tukey method.* Applying this procedure we note that the range of the 5 means F, D, A, B, C is 94 and that this is less than the allowance 96.7 . Hence we do not conclude that the means of this subgroup differ significantly. Analysis in this direction stops. Start now at the other end. Here we have D, A, B, C, and E with a range of 102. We therefore conclude that the means of this group are significantly different and further analysis at this end is waranted. Consider next the 4 mean group A, B, C, and E. The range of these means is 98 and again this exceeds 96.7, so we conclude that the means of this group also differ significantly. A further subdivision is in order. The next subgroup of means is B, C, and E which has a range of 72; but 72 is less than 96.7 so we conclude that these means do not differ significantly.

We can summarize the results in the following diagram:

F D A B C E

Thus we conclude that F, D, and A are less than E, but that B and C may be the same as E. We also conclude that C, B, A, and D may be the same as F. "

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* Cf. John W. Tukey, " The Problem of Multiple Comparisons", unpublished dittoed notes, Princeton University, 1953.

"VITA"

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